ColorBless: Augmenting Visual Information for Colorblind People with Binocular Luster Effect

SOON HAU CHUA, HAIMO ZHANG, MUHAMMAD HAMMAD, SHENGDONG ZHAO, and SAHIL GOYAL, National University of Singapore
KARAN SINGH, University of Toronto

Binocular disparity allows interesting visual effects visible only to people with stereoscopic 3D displays. Here, we studied and applied one such effect, binocular luster, to the application of digital colorblind aids with active shutter 3D. We developed two prototype techniques, ColorBless and PatternBless, to investigate the effectiveness of such aids and to explore the potential applications of a luster effect in stereoscopic 3D beyond highlighting. User studies and interviews revealed that luster-based aids were fast and required lower cognitive effort than existing aids and were preferred over other aids by the majority of colorblind participants. We infer design implications of a luster effect from the study and propose potential applications in augmented visualization.

Categories and Subject Descriptors: H.5.2 [**Information Interfaces and Presentation**]: User Interfaces—*Screen design*

General Terms: Design, Experimentation, Human Factors, Performance

Additional Key Words and Phrases: Binocular luster, stereoscopic 3D, color blindness, augmented visualization

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1. INTRODUCTION

Color blindness is a medical condition that affects approximately 200 million people globally [Anon 2001]. Color blindness is characterized by the impaired ability to distinguish certain colors in the human color spectrum. There are three main types of colorblindness in humans: protan, deutan, and tritan, each corresponding to defect in red, green, and blue cones, respectively. The severity of the defect has two levels: *dichromacy*, in which the cone is absent or not functioning, and *anomalous trichromacy*, in which the cone's spectral sensitivity is altered but still functioning. Both protan and deutan are considered as red-green color blindness whereas tritan is blue-yellow colorblindness. According to Deeb, approximately 8% of men and 0.5% of women among

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Authors' addresses: S. H. Chua, H. Zhang, M. Hammad, S. Zhao, and S. Goyal, COM2-01-05 School of Computing, National University of Singapore, 13 Computing Drive, Singapore 117417, Republic of Singapore; emails: chuasoonhau@nus.edu.sg, haimoz@acm.org, m.hammadpk@gmail.com, zhaosd@comp.nus.edu.sg, sahil.iitg@gmail.com; K. Singh, Computer Science, University of Toronto, 40 St. George Street, Toronto, Ontario, Canada M5S 2E4; email: karan@dgp.toronto.edu.

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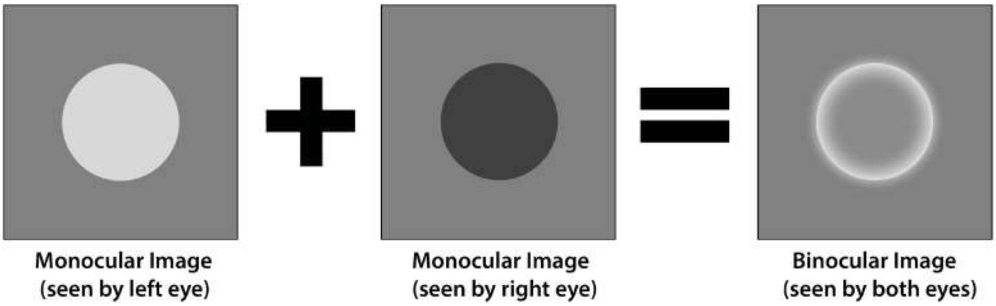

Fig. 1. Visual illustration of the binocular luster effect.

people with Northern European ancestry who suffer from red-green colorblindness [Deeb 2005].

Existing digital aids help people distinguish colors by either substituting colors with those of higher contrast or applying visual patterns on top of confusing colors to augment visual information. Although useful, both have their own sets of limitations in actual usage [Sajadi et al. 2012]. We propose two techniques to overcome some of their limitations based on an effect in binocular vision.

Human vision utilizes the optical parallax effect between two eyes to create binocular disparity, thus allowing our brain to perceive depth in everyday life. In addition to enabling stereopsis, varying the monocular images seen by each eye can create interesting visual effects such as binocular rivalry, the sieve effect, floating effect, and binocular luster effect [Formankiewicz and Mollon 2009]. Traditionally, these effects can only be explored in the laboratory setting. However, with the advent of stereoscopic 3D technology, it is now possible for people to experience binocular disparity with 3D-enabled displays, thus opening up potential opportunities to expand the functionality of stereoscopic devices beyond watching 3D content. Recent popularity of this technology in the consumer market has piqued researchers in Human-Computer Interaction (HCI) and computer graphics to investigate the potential usage of binocular disparity in the applied domain, including highlighting, composition, information hiding, wowing [Zhang et al. 2012], and enriching visual richness in photos [Yang et al. 2012].

We are interested in the application of one such effect, the binocular luster effect, in the HCI domain. Binocular luster effect is the visual perception of salient shininess produced by the presence of brightness differences between the two monocular images we see in each eye, relative to the background, as illustrated in Figure 1 [Howard 2002]. Binocular luster is one of the most salient visual phenomena [Tyler and Scott 1979]. Although it has been recently applied to produce highlights in 3D images [Zhang et al. 2012], its perceptual strength as a function of color, contrast, and difference in brightness has not been measured.

Like hue and saturation, the luster effect could be used in visual encoding to represent information, especially for users with an impaired ability to perceive other encoding variables. Indeed, selective filter lens, such as X-Chrom lens, have been used to create brightness difference between the two eyes to help colorblind people in distinguishing hues [Sheedy and Stocker 1984]. In spite of that, there is a lack of evidence indicating that such lens could distinguish color in all situations, and it has been shown to impair depth perception in users [Hartenbaum and Stack 1997].

In this article, we propose two prototypical colorblind techniques that apply binocular luster effect in separate ways to augment visual information for colorblind people. We conducted a user study with 10 deutan colorblind participants to compare our approaches with two different digital colorblind aids and found that our approaches are faster and require less cognitive effort in decoding color information. A majority of colorblind participants also prefer our approaches. Last, perceptual observations from our study suggest strong potential for using binocular luster effect for unobtrusive information visualization overlays.

Our contribution with this article is threefold:

—We provide a set of basic implementation guidelines for applying binocular luster with stereoscopic 3D by conducting basic psychophysical studies.
—We designed and implemented two prototypical luster-based colorblind techniques, ColorBless and PatternBless, and conducted a user study to determine the usability and practicality of stereoscopic luster-based aids.
—We propose potential applications of the binocular luster effect in the HCI application domain based on implications from our study.

2. BACKGROUND AND RELATED WORK

To provide a better understanding of the main topics discussed in this article, we reviewed previous work on *existing colorblind aids* and *binocular luster* and present them in this section.

2.1. Existing Colorblind Aids

In general, there are three strategies for colorblind people use to distinguish confusing colors. They are (i) contextual inferences, (ii) substituting colors, and (iii) augmenting visual information.

2.1.1. Contextual Inferences. Contextual inferences rely on the ubiquitousness of a commonplace object to convey color information. The most notable example is the traffic light, where the positioning of the lights infers color information. The traffic light model has been used in other places, such as the Mac OS X operating system, to indicate closing (red), minimizing (yellow), and maximizing (green) of windows. However, many objects do not have a consistent and universal color use, which limits the usefulness of this strategy in daily life.

2.1.2. Substituting Colors. Colorblind aids in this category substitute confusing colors with other colors to enhance color contrast for colorblind users. This can be achieved in two ways: from the content creator's end by using a colorblind-friendly color scheme (known as prepublication aids), and by changing the colors of the contents after they have been created (known as postpublication aids).

Prepublication aids are not widely adopted for several reasons. One is that it limits the color palette that a content creator can use in content design. Second, it disrupts the semantic meaning of the colors that normal color vision populations are familiar with. We see the problem as a three-way tradeoff between the content creator's need to express creative or semantic meanings with colors, colorblind people's need to decode color information reliably, and, finally, the need of normal color vision people to capture the semantics of colors accurately.

Thus, there is a need for postpublication aids that allow colorblind users to resolve color confusion for themselves. One physical solution is to wear lenses such as X-Chrom lenses and EnChroma Cx that change the wavelength of receiving light [Sheedy and Stocker 1984]. Although X-Chrom lenses enhance color contrast, they alter the color perception of the user's entire vision, which changes the perceived hue of those colors that are initially not confusing to them. In addition, their efficacy in distinguishing colors in different situation was largely unproved and could potentially impair users' depth perception [Hartenbaum and Stack 1997]. Although EnChroma Cx does not impair depth perception and is usable under broad daylight, its usage is problematic with certain indoor lighting and computer screens.

Regarding digital solutions, most postpublication aids focus on enhancing color contrast by recoloring the original to a different color. Many related works on recoloring techniques have been proposed in this category. Daltonize, one of the earliest and most widely used, works by increasing the red/green contrast, brightness, and blue/yellow coloration in images [Dougherty and Wade 2009]. Wakita and Shinamura proposed a recoloring technique that allows "author's intention" to be preserved in documents by adjusting the mapping algorithm [Wakita and Shimamura 2005]. In comparison with these two works, Rasche et al. focused on the differences between confusing color pairs rather than the similarity of mapped colors to the original ones [Rasche et al. 2005]. Kuhn et al. presented an automatic and efficient technique that preserves the naturalness of colors [Kuhn et al. 2008]. Jefferson and Harvey created a recoloring algorithm that computes the target color distances according to the World Wide Web Consortium (W3C) and Web Accessibility Initiative (WAI) [Jefferson and Harvey 2006]. In the following year, the same authors followed up with another recoloring algorithm that transfers the chromatic variation of the defective cone onto two other functioning cones [Jefferson and Harvey 2007]. A similar color compensation technique was proposed slightly later, which converts RGB color space to HLS color space to avoid defective color ranges [Ohkubo and Kobayashi 2008]. Machado and Oliveira presented an automatic recoloring technique that preserves temporal coherence [Machado and Oliveira 2010]. Recently, a Situation-Specific Model (SSM) of color differentiation was proposed to address the limitations of existing recoloring techniques on a carefully controlled viewing environment [Flatla 2011].

Some of the recoloring algorithms have been incorporated into existing software and mobile applications. For example, Chrome Daltonize!,[1] a plugin for the Google Chrome browser, applies Daltonize to resolve color confusion in webpages. On mobile devices, augmented reality applications such as DanKam[2] apply filters created from Daltonize and other techniques to the phone's camera feed and images. Very recently, Daltonize was also applied to a Google Glass system as a filter of the real-time scene captured by the Glass's camera feed [Tanuwidjaja et al. 2014].

Although much work has been done on improving recoloring techniques, there remain limitations. First, they are not very effective in resolving color ambiguities with images that contain many colors [Sajadi et al. 2012]. As a color is changed, the resulting color could potentially be confused with other existing colors in the image. Second, recoloring techniques inadvertently affect the color perception of normal color vision people since the underlying original colors are changed. Therefore, they are not very effective in scenarios where colors convey semantic meanings and are seen by both normal and colorblind people.

2.1.3. Augmenting Visual Information. Unlike recoloring techniques, augmentation aids append additional visual elements such as shapes, positions, line types, and different patterns onto the image to augment visual information. In charts, these elements could be added to assist in interpreting data other than colors. An example here is the ColorAdd® Color Identification System[3] that uses five simple symbols to represent different colors. These augmentative visual elements are added in a prepublication manner. Unfortunately, prepublication strategies are not widely implemented and standardized in the industry.

Recently, one approach has demonstrated the use of patterns to encode color information for colorblind users in a postpublication manner [Sajadi et al. 2012]. Their

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[1] http://www.daltonize.org/.

[2] http://dankaminsky.com/2010/12/15/dankam/.

[3] http://www.coloradd.net.

technique overlays patterns on images in a content-independent manner without recoloring the images. Because line patterns of different slopes are applied to different colors, this method can be used to identify colors instead of just distinguishing them, which minimizes ambiguities in the decoding process. However, although the colors are not recolored, this approach overlays line texture on top of colors in such images. Recognizing patterns (with different slopes) to distinguish colors might require higher cognitive effort, which slows down the color decoding process.

2.2. Binocular Luster

Binocular luster effect is characterized by the perception of metallic shininess on an object in our binocular vision [Howard 2002]. Luster can be seen when there are enough differences in brightness on the same object relative to the background. When binocular brightness disparity is larger than the binocular fusion limit, noticeable alternation between left and right images takes place in human vision, making the object appear shimmering to viewers [Levelt and others 1968]. Human eyes are capable of perceiving a luster effect rapidly, making the effect intensely salient [Bal et al. 2011] and uncomfortable at times [Kooi and Toet 2004].

Binocular luster has been studied in the context of visual perception [Formankiewicz and Mollon 2009; Pieper and Ludwig 2002; Yoonessi n.d.]. A significant characteristic of a luster effect in HCI is the ability to create different levels of perceived shininess to represent ordinal data. The perceived intensity of the luster effect can be influenced by several factors. The primary factor is the object's brightness disparity between the left and right eyes [Ludwig et al. 2007], in which larger disparity increases the shininess of the effect. The second factor is the contrast polarities between the luster region and its background [Anstis 2000], in which the effect is stronger in stereo images with opposite contrast polarity in their monocular images. As illustrated in Figure 1, shininess is more perceivable on the circle in the binocular image because the circle in the left monocular image has a higher luminance than its background, whereas the one on the right has a lower luminance, thus forming opposite contrast polarities between monocular images. A third factor is the size of the lustered object, in which bigger size has been associated with higher shininess [Pieper and Ludwig 2001].

Although modern stereoscopic technology has enabled such effects to be presented to the average audience, the application of a luster effect is still limited. Recently, Zhang et al. proposed the use of luster for highlighting to make objects in 3D images more noticeable to the viewer [Zhang et al. 2012]. In this article, we investigate the viability of using this effect to augment color information for colorblind users.

3. DESIGNING LUSTER-BASED DIGITAL COLORBLIND AIDS

Motivated by the unique characteristics of binocular luster effect that could potentially overcome some of the limitations in existing colorblind aids, we conducted a thorough investigation on the viability of using this effect as a postpublication colorblind aid and proposed two techniques that apply a luster effect with active shutter 3D to augment visual information in images. The first technique, ColorBless, encodes color information by first determining confusing color pairs in an image and then applying a luster effect to one of the colors. With ColorBless, a colorblind person uses a luster effect applied on colors as a visual cue to tell confusing colors apart. Unlike physical luster-based aid like X-Chrom lens, ColorBless applies a luster effect to the confusing color regions only, not to the entire scene. The second technique, PatternBless, applies a luster effect in the form of shiny patterns onto colors as a way to augment visual information in an image.

For the two techniques to be usable and more efficient than some of the existing aids in an actual setting, the techniques need to fulfill three design requirements based on the limitations of existing aids and the characteristics of a luster effect. First, the color distinguishing speed has to be fast. Second, it should minimize the underlying color change. Third, the luster effect should be perceivable at a comfortable level. Based on the design requirements and our motivation, stated in the beginning of this section, we propose the following research questions:

RQ1: What are the luminance difference (dY) levels required for the luster effect to be just noticeable and comfortable? What are the possible factors that could affect the two based on previous work in physical studies?

RQ2: Compared to the Daltonize recoloring technique [Dougherty and Wade 2009] and pattern technique [Sajadi et al. 2012], is applying binocular luster with active shutter 3D an effective way to augment visual information while minimizing underlying color change?

RQ3: What are the subjective evaluations of ColorBless and PatternBless compared to the recoloring and pattern techniques? Which colorblind aids would colorblind users prefer in several common use-case scenarios?

User studies were conducted to evaluate ColorBless and PatternBless based on these three design requirements and research questions. The next section elaborates the implementation of both techniques and how color change is minimized at the algorithm level.

4. IMPLEMENTATION

To implement a luster effect as an augmentation aid for colorblind people, an algorithm that determines the pixels to be applied luster and a program that applies the luster are required. The following sections describe how we identify regions with confusing colors in an image, our luster-applying strategies for the ColorBless and PatternBless techniques, and how we apply the luster effect. A flowchart diagram of all the steps involved is illustrated in Figure 2.

4.1. Identifying Clusters of Confusing Colors

The first step in the algorithm is to determine colors in an image I that are confusing to colorblind people. To do this, we apply the colorblind simulation algorithm developed by Meyer and Greenberg to determine those pixel regions that get transformed into the same color in the simulated image [Meyer and Greenberg 1988]. This algorithm transforms image I to an image *cb_sim(I)* by reducing to a single color those colors that lie along the dichromatic confusion line (the line parallel to the axis of the missing photoreceptor). In the CIE1931 color space, the colors along the confusion line, which is different for protan, deutan, and tritan, are indistinguishable for colorblind people. This algorithm identifies the confusing color regions in image I.

To cluster key colors in *cb_sim(I),* we adopted an approach similar to that used by Huang et al., but instead of applying affinity propagation, we used mean shift clustering together with K-means clustering [Huang et al. 2010]. After obtaining the simulated image, we apply mean shift clustering to the simulated image *cb_sim(I)* to classify the pixels into clusters of similar color [Comaniciu and Meer 2002]. We use a combination of pixel distance and the CIE color distance metric to define cluster distance and a default mean-shift “bandwidth” parameter of 0.05. Larger bandwidth generates fewer and bigger spatial clusters of similar color and vice versa. Although each cluster in the simulated image *cb_sim(I)* represents a single color, the pixels belonging to the cluster have various values along a confusion line in the original image I. For example red and green pixels in I may have been transformed into a single color cluster in *cb_sim(I)*, and it is these colors that we now wish to distinguish in I using binocular luster. For the pixels in each cluster, we now apply k-means clustering on the pixel colors of the

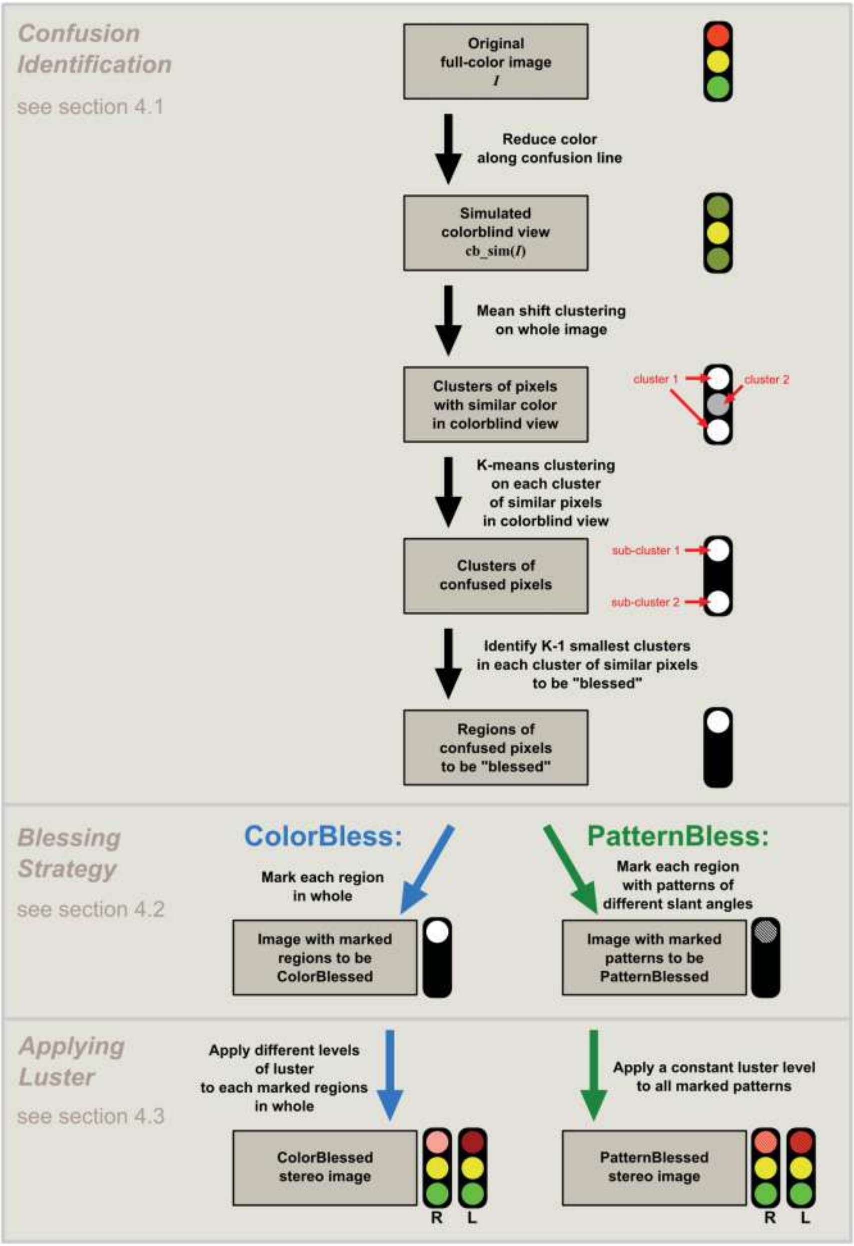


Fig. 2. Flowchart and illustration of the implementation of the ColorBless and PattenBless techniques.

original image I to separate each cluster of confusing colors into k discrete sets. For example, if we only wish to distinguish two primarily confused colors we set $k = 2$.

4.2. Blessing Strategies

4.2.1. ColorBless Technique. For the ColorBless technique, we distinguish the k sets by applying k-1 different levels of binocular luster to k-1 smallest sets, leaving the largest set of prevalent color in image I unaltered (no luster). Our studies later show that up to three different levels of binocular luster can be perceived (i.e., a value of $k \leq 4$ can be used).

4.2.2. PatternBless Technique. PatternBless applies lustered striped lines of different patterns with the same luster intensity onto different confusing color regions in the image to provide augmented color information. We compute pixel regions corresponding to the k sets of color that we would like to distinguish following the algorithm presented in Section 4.1. After applying k-means clustering, we then map the hue of each of the representative k colors to a line slant ϕ, which can qualitatively convey the hue in a region. Then, we use the size of the clustered region's bounding box to define spacing s of the line stripes. Finally, we apply a luster effect to the pixels after rotation by an angle of ϕ, lie on horizontal lines that are s pixels apart.

4.3. Applying Luster Effect

To apply the luster effect, we convert the RGBs of a JPEG image into YUV color space, in which the Y component controls the luminance and U and V control the chrominance components. Then, two images are created: one for left eye and other one for right eye. One image is created by increasing the Y component on the targeted pixel locations, and the other is created by decreasing the Y component on the same pixel locations. To minimize the underlying color change, the Y component of both images is increased and decreased by the same value:

$$leftImage_{i,j} \leftarrow YUVImage_{i,j}.Y - dY, rightImage_{i,j} \leftarrow YUVImage_{i,j}.Y + dY,$$

where $YUVImage$ represents the original image in YUV color space, dY represents the brightness differences created on the targeted pixels, $leftImage$ represents the image for left eye, and $rightImage$ represents the image for right eye. The two images are then combined to generate a 3D image file viewable with a 3D setup.

5. STUDY METHODOLOGY AND DESIGN

A user study was performed to compare and evaluate the ColorBless and PatternBless techniques against other existing postpublication aids. As comparisons against our approaches, we chose the Daltonize recoloring technique [Dougherty and Wade 2009], which substitutes color and is also the most widely used of such techniques, and the pattern technique developed by Sajadi et al. [2012] that augments color information with line patterns of different slopes.

5.1. Experimental Design and Protocol

The user study was divided into four sections. The first section (S1) investigates the binocular luster effect with active shutter 3D, which answers RQ1. Both normal color vision and colorblind participants were assigned to S1 to determine if there are any differences in just-noticeable and comfortable dY between normal and colorblind people. The second section (S2) investigates the color distinguishability of each colorblind technique, which answers RQ2; this condition was assigned only to colorblind participants. The third section (S3) investigates the color differences produced by the colorblind techniques, which answers RQ2; this condition was assigned only to normal color vision participants to study how their color perception would be affected. Finally, the fourth section (S4) answers RQ3 by acquiring subjective evaluation of the usage of the four colorblind techniques; this condition was assigned only to colorblind participants. The details of each study section are described in the following sections.

5.1.1. Section 1 (S1): Investigating Luster in Active Shutter 3D. The goal in S1 was to determine the average just-noticeable brightness differences (dY) levels, the average comfort threshold dY level, and the average number of discrete luster levels that participants

Fig. 3. Nine nonluster stimuli images in S1. Three different colors and backgrounds (with different luminance Y values in the YUV color space) were applied, respectively.

can differentiate between the just-noticeable and comfort threshold dY levels. In addition, we also looked at the effect of different colors, contrast polarity, and participants' color vision (normal and colorblind) on the three dependent variables.

Nine nonluster stimuli images (Figure 3), each with 10 luster variants ($dY = 10$, 20, 30, 40, 50, 60, 70, 80, 90, 100) that constitute a total of 99 stimuli images, were presented to each participant; in each image, a luster effect was applied to the square in the middle of the image (Figure 3). To create stimuli with different contrast polarity, we varied the luminance Y values of the background in YUV color space (Y = 18,128,238) to create three variants for each color (from left to right in Figure 3). Y values of the colors in squares were kept constant at 128 for all stimuli. Hence, contrast polarity is present in stimuli with background of Y = 128, and no contrast polarity is present in stimuli with background of Y = 18 and Y = 238. Examples of stimuli images with blue squares in Figure 3 can be found in Supplementary Package 1.

Participants were asked to answer three questions for each stimulus shown. The first is a yes/no question of whether they can perceive a luster effect on the colored square. The second is a 10-point Likert scale rating on the saliency of the luster effect, with 1 being not visible at all and 10 being extremely salient. The third is a 5-point category rating scale of the experienced viewing comfort for the luster image relative to the nonluster image. In this scale, 1 point represents equal viewing comfort with the nonluster image and 5 represents extremely reduced viewing comfort. This scale was previously used by Kooi et al. to investigate the visual comfort of 3D displays [Kooi and Toet 2004].

For each set of stimuli (e.g., 11 images of blue with background of Y = 128, dY from 0 to 100), just noticeable dY is determined by the lowest dY level at which participants indicated *yes* in the first question. Comfort threshold dY is determined by the highest dY level at which participants rated a 2 for the experienced viewing comfort level, a threshold also used by Kooi et al. in their work [Kooi and Toet 2004]. The number of discrete luster levels was determined by presenting the stimuli between just-noticeable dY and comfort threshold dY to the participants and asking them to indicate the number of perceptually different luster levels among the stimuli shown.

When presenting each stimuli set, the nonluster stimulus was always shown first, followed by stimulus with $dY = 100$ to give participants a sense of the maximum luster levels. Then, the presenting sequence of those stimuli with dY between 0 and 100 were randomized; participants were unaware of the dY level of the stimulus shown. The

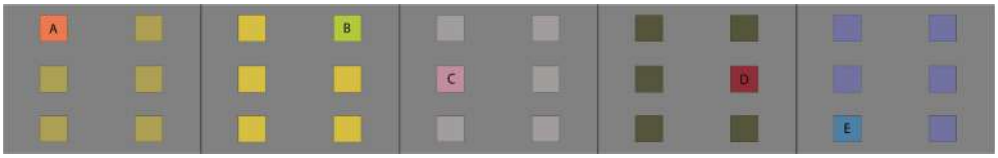


Fig. 4. Stimuli used in S2. The different colors in each stimulus, A to E, were used in S3 (the letters in this figure were not shown in the actual stimuli).

nonluster stimulus was always shown on the right side of the display to facilitate the answering of the questions.

5.1.2. Section 2 (S2): Measuring Color Distinguishability. To measure the color distinguishability of the colorblind techniques (recoloring, pattern-applying, ColorBless, PatternBless), participants were told to indicate the square with a different color in the stimuli images presented in Figure 4. Their responses and color Distinguishing Time (DT; timer starts when the image appears and ends when the participant indicates his or her response) of each stimulus image were recorded with a key press. Numbers 1, 2, 4, 5, 7, 8 on a number pad were chosen due to their correspondence to the positions of the colored squares in the stimuli. Stimuli images shown in Figure 4 can be found in the Color Distinguishing Stimuli folder in Supplementary Package 2.

Five confusing color pairs were prepared for this part of the experiment (Figure 4). A pre-test was done to determine the three color pairs that were the most confusing for each colorblind participant. During pre-test, each participant was instructed to quickly point out the color square that was a different color from the rest for each of the five stimuli. We picked three stimuli in which the responses were either incorrect or delayed. In each actual trial, subjects were told to indicate the square with a different color using number pad.

A within-subject design was used in which each participant encountered four groups of stimuli in which each of the four techniques was applied. An additional group of stimuli with original, untouched images was included in this section to ensure that the colors were confusing for participants. The presenting sequence of stimuli blocks, where one block represents a colorblind technique, was counterbalanced across participants using a Latin square. Within each stimuli block, there are 18 stimuli images with three different confusing color pairs and six possible square positions ($3 \times 6 = 18$ stimuli). Square positions were also counterbalanced to prevent ordering effects.

To investigate effectiveness of the techniques in chart images, we also measured participants' response time in solving tasks in bar, pie, and line graphs with confusing colors. To accommodate five conditions (untouched, recoloring, pattern-applying, ColorBless, and PatternBless), five variants for each type of graph (e.g., bar, pie, and line) were designed with different data but with the same number of data categories and colors. An example of the bar graphs used in the study is shown in Figure 5. The five variants were controlled with the same number of data categories and colors used. The Latin square was used to counterbalance the presenting sequence of technique-applied stimulus across participants. Examples of bar graph images used in this section, including the untouched, Daltonize, ColorBless, and PatternBless, can be found in the Bar Graph Stimuli folder in Supplementary Package 2.

The dependent variables in this section were Error Rate (ER) and task completion time. ER was defined by the number of wrong responses over the total responses in each block. Color DT was measured in the color distinguishing tasks (with stimuli shown in Figure 4), whereas the Reaction Time (RT) was measured in completing the task in the chart stimuli (with stimuli shown in Figure 5).

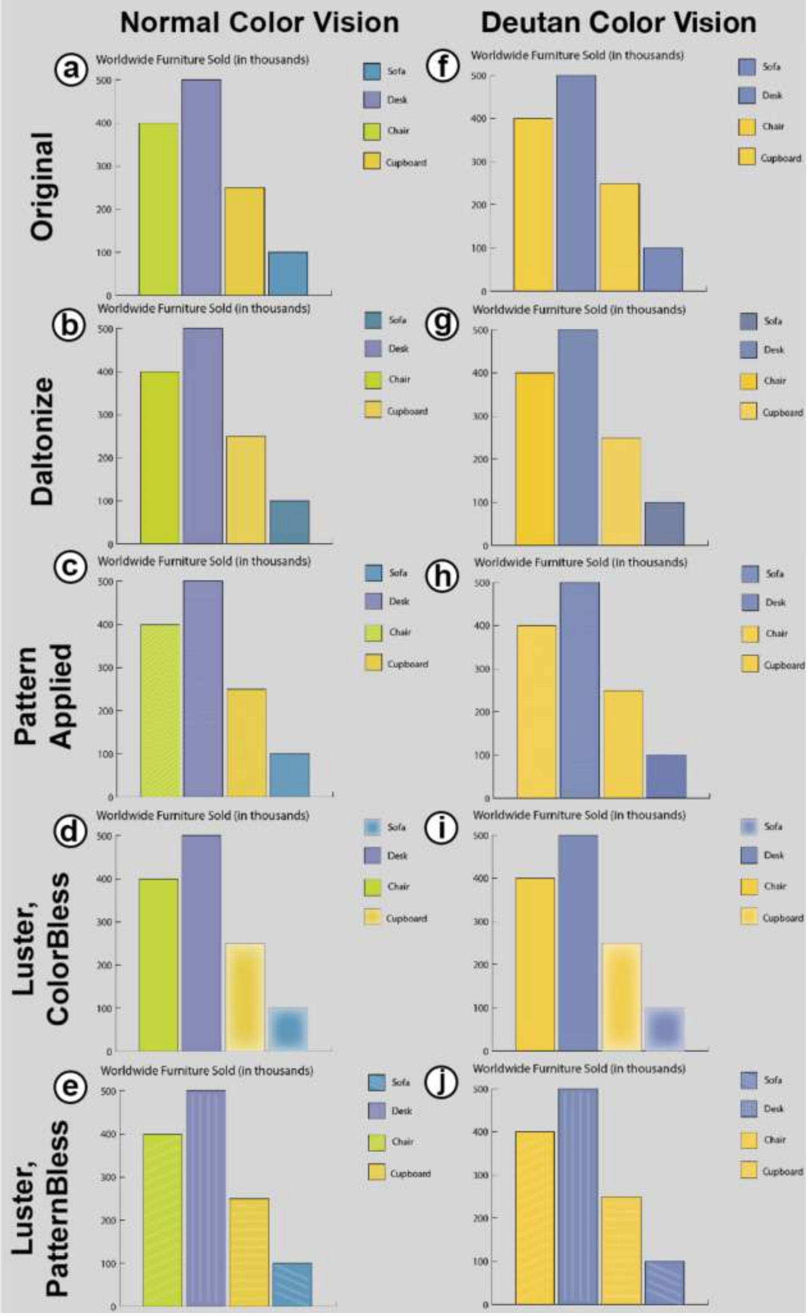
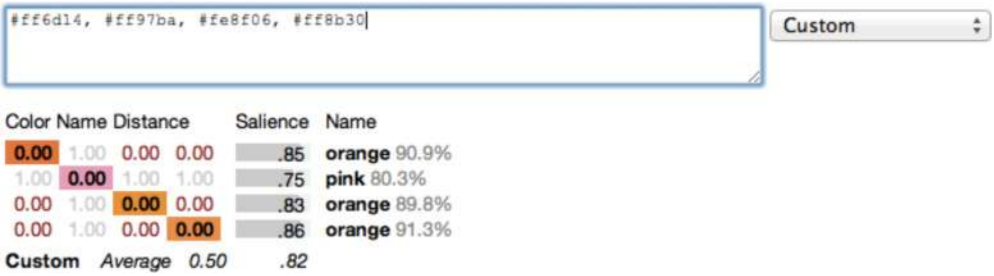


Fig. 5. An overview of the effects of the four colorblind aids. Graph images on the left represent the colors seen by people with normal color vision; images on the right are the colors seen by deutans; (a) and (f) are original, untouched images; (b) and (g) are images recolored by Daltonize technique (note the darker shade on Sofa and lighter shade on Cupboard); (c) and (h) are images augmented with patterns; (d) and (i) are images with a luster effect (ColorBless); and (e) and (j) are images with lustered patterns (PatternBless). Note that images (d, e, i, j) in this figure are for illustrative purposes. The actual stereo images with a luster effect can be found in the Bar Graph Stimuli folder in Supplementary Package 2 that accompanies this article.



`#ff6d14, #ff97ba, #fe8f06, #ff8b30`

Custom

Color Name Distance				Salience	Name
0.00	1.00	0.00	0.00	.85	**orange** 90.9%
1.00	0.00	1.00	1.00	.75	**pink** 80.3%
0.00	1.00	0.00	0.00	.83	**orange** 89.8%
0.00	1.00	0.00	0.00	.86	**orange** 91.3%
Custom	*Average*	*0.50*		*.82*	

Fig. 6. An instance of Color Palette Analyzer [Heer and Stone 2012] used in our study to evaluate the color differences of the recolored, pattern-applying, and lustered techniques from the original color based on their respective pairwise color name distances. The color palette and the hex values in the figure, in left to right order, belong to color A altered by the original, recolored, pattern-applying, lustered techniques.

5.1.3. Section 3 (S3): Evaluating Color Differences. Perceptual color differences produced by the recoloring, pattern, and luster-based aids were evaluated by normal color vision participants. We selected five colors from the stimuli used in S2, as indicated by A, B, C, D, E in Figure 4. The RGB hex values of colors A, B, C, D, and E are #F77B4D, #B8D232, #C790A4, #952C37, and #4E84AC, respectively. Participants were told to evaluate the color differences between the original color and the modified color.

Color name distance, a measure of similarity between colors based on naming patterns created by Heer and Stone in CHI 2012 [Heer and Stone 2012], was used to evaluate the perceived color differences because people associate a color's name with its semantic meaning. To measure color name distance, the participants were first asked to name and input the colors in the Color Dictionary.[4] The Color Dictionary was constructed within the standard CIELAB color space, and its color distance metric was constructed with the current standard CIEDE2000 because RGB color space is a poor model with which to study human color perception [Heer and Stone 2012]. Then, participants were told to choose one RGB hex value from the 20 palettes presented (or from additional palettes in similar colors) that best matched the color being evaluated. After all responses were collected, the RGB hex values of the perceived original and modified (recoloring, pattern, and luster-based) colors were inputted into a Color Palette Analyzer[5] to calculate color name distance from the original color, as shown in Figure 6.

5.1.4. Section 4 (S4): Subjective Evaluation. A post-study questionnaire and interviews were conducted with colorblind participants to evaluate the four techniques used in this study. The questionnaire and interviews were conducted after the participants completed Sections S1 and S2 of the user study. All responses were recorded in person, using Google Form.

First, each technique was evaluated individually with a 5-point Likert scale based on four metrics, including perceived distinguishing speed, cognitive effort required to distinguish colors, comfort level, and obviousness of the effects. An example of the question used to evaluate ColorBless's comfort level in distinguishing confusing colors is: "Rate the comfort level of using ColorBless to distinguish confusing colors," followed by a 5-point Likert scale with 1 representing "not comfortable at all" and 5 representing "very comfortable." After evaluating the techniques, participants were asked to indicate their most preferred colorblind technique in several common use-cases when working with charts. These use-cases include working alone, working collaboratively with normal color vision people, working alone with figures containing many colors,

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[4] http://vis.stanford.edu/color-names/dictionary/.

[5] http://vis.stanford.edu/color-names/analyzer/.

Table I. Average Just-Noticeable dY, Comfort Threshold dY, and Number of Discrete Luster Levels for Normal Color Vision and Colorblind Participants when Encountering Stimuli with Same Contrast Polarity and Opposite Contrast Polarity

	Normal (N = 10)		Colorblind (N = 6)	
	Same Contrast Polarity	Opposite Contrast Polarity	Same Contrast Polarity	Opposite Contrast Polarity
Just noticeable dY	25	13.66	21.66	10.55
Comfort threshold dY	62.33	50.66	58.61	33.88
Number of Luster levels	3	3	3	3

and working collaboratively with figures containing many colors. The four working use-cases came from a pilot interview with colorblind participants to understand the circumstances in which colorblind aids would most likely be used in real life. The colorblind participants' preferences in these use-cases were collected using multiple-choice questions in which only one technique can be chosen. In the end, brief interviews were conducted to understand their needs and common issues in decoding color information from digital content.

5.2. Participants

Ten colorblind and 10 normal color vision participants aged 21–30 were recruited from the host university. All participants have normal or corrected-to-normal vision. Colorblind screening test was done with HRR Pseudoisochromatic Plates with all participants before the studies to verify their color vision. The colorblind severity of all participants was tested and found to be either mild or medium deutans with HRR Plates. Colorblind participants were recruited for Sections S1, S2, and S4 of the user study, whereas normal color vision people were recruited for Sections S1 and S3.

5.3. Materials

Binocular luster effect can be created with a glass-based 3D-ready setup ranging from active shutter, passive polarized, to Dolby 3D systems. In our user study, the techniques were realized using the active shutter 3D-enabled Alienware M17x laptop equipped with NVIDIA 3D Vision (GPU: NVIDIA Geforce GTX 560M). Spyder 4Pro was used to calibrate the color of the laptop's 3D display to ensure accurate color representations.

6. RESULTS

6.1. S1: Investigating Binocular Luster in Active Shutter 3D

Two-way repeated-measures ANOVA were used to analyze the effects of colors and contrast polarity on three dependent variables: just-noticeable dY, comfort threshold dY, and the number of discrete luster levels. The data in S1 are summarized in Table I. In terms of just-noticeable dY, there is a significant effect in contrast polarity ($F_{1,9} = 41.78$, $p < 0.001$), indicating that contrast polarity influences the noticeability of the luster effect. Stimuli with opposite contrast polarity have a lower just-noticeable dY (13.66) than do stimuli with the same contrast polarity (25). However, no similar significant effect is observed for color ($p > 0.05$), indicating that the colors used in the user study did not affect just-noticeable dY. The same conclusion can be made for colorblind participants (data not shown). For comfort threshold dY, we noticed a similar statistically significant effect for contrast polarity ($F_{1,9} = 23.457$, $p < 0.01$) but not with color ($p > 0.05$). Again, stimuli with opposite contrast polarity have a lower comfort threshold dY (50.66) than do stimuli with same contrast polarity (62.33). Same significant trend can be seen for the colorblind participants (data not shown).

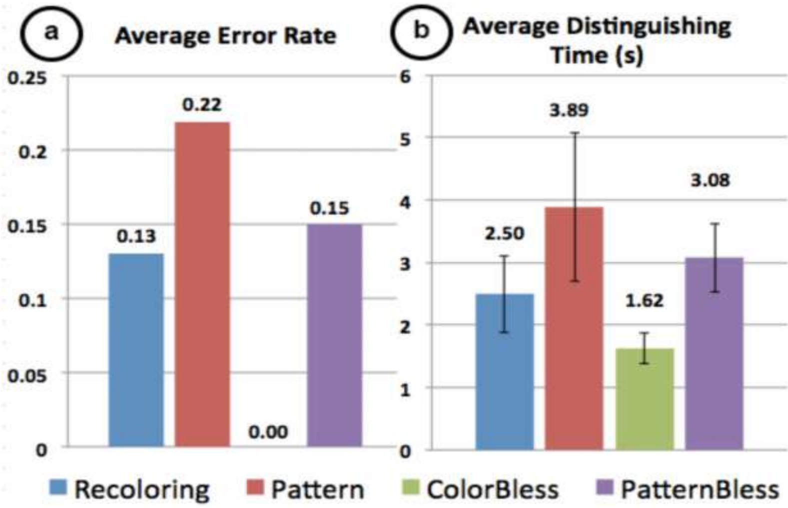

Fig. 7. (a) Average Error Rate (ER) and (b) Distinguishing Time (DT) of the 10 colorblind participants in completing simple color distinguishing tasks. Error bars represent standard deviation.

Table II. Error Rate and Reaction Time (in Seconds) of Using Different Colorblind Techniques in Solving Tasks in Graphs

	Recoloring		Pattern		ColorBless		PatternBless	
	ER	RT	ER	RT	ER	RT	ER	RT
Bar	0.20	5.56	0	5.92	0	5.84	0	6.27
Pie	0.20	5.07	0	5.46	0	4.89	0.11	6.17
Line	0.60	9.14	0.60	11.84	0.25	10.02	0.22	9.93

However, for the number of discrete luster levels differentiable (by normal color vision participants), no significant effects were observed in either contrast polarity ($p > 0.05$) or colors ($p > 0.05$). Participant color vision does not affect this conclusion (data not shown for colorblind participants). All participants can reliably differentiate three levels of a luster effect between just-noticeable dY and comfort threshold dY.

6.2. S2: Measuring Color Distinguishability

Figure 7(a) shows the average ER of the four techniques in color distinguishing tasks. Repeated-measures ANOVA determined that there is an overall significant difference between mean ERs for the four techniques ($F_{3,\,27} = 4.481, p < 0.05$). However, pairwise comparison with Bonferroni correction only shows statistically significant difference between the ColorBless (0.00) and pattern techniques (0.22), indicating that ColorBless produces significantly less error than the pattern technique ($p = 0.034$), whereas difference between ColorBless (0.00) and recoloring (0.13) is not significant ($p = 0.15$).

In terms of DT, there is an overall significant difference between the means of different techniques after Greenhouse-Geisser correction ($F_{1.623,\,12.514} = 19.637, p < 0.0005$). Average distinguishing time is shown in Figure 7(b). Post-hoc tests using the Bonferroni correction revealed that ColorBless (1.62s) is faster than other techniques with statistical significance (recoloring is 2.5s with $p < 0.01$, pattern is 3.89s with $p < 0.001$, PatternBless is 3.08s with $p < 0.001$), and recoloring (2.5s) is faster than pattern (3.89s) ($p = 0.02$). No significant differences are found in other pairwise comparisons.

Table II shows the ER and response time of solving tasks in different graphs. There are no overall significant differences in the response times of solving tasks in bar ($p = 0.752$), pie ($p = 0.461$), and line ($p = 0.458$) graphs. Referring to Table II, the ERs

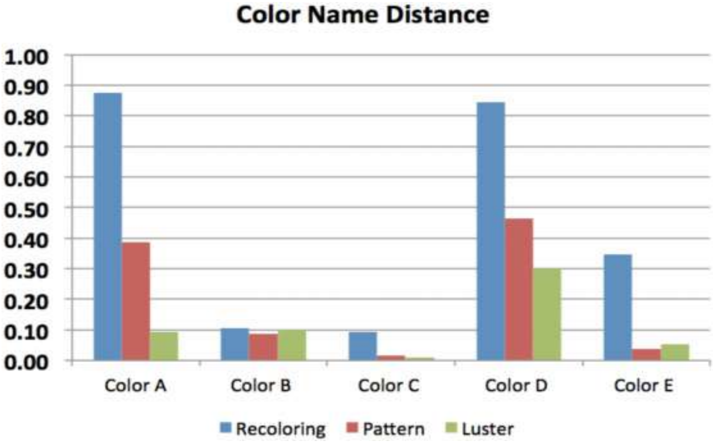

Fig. 8. Color name distance of original color vs. modified color with recoloring, pattern, and luster (ColorBless).

of the pattern, ColorBless, and PatternBless techniques are lower than the recoloring technique in bar and pie charts. Interestingly, for line charts, the ERs for both recoloring and pattern technique are very high (both 0.60) compared to ColorBless (0.25) and PatternBless (0.22).

6.3. S3: Evaluating Color Differences

Figure 8 shows the average color name distance of each technique, where higher values represent a larger color differences. Using repeated-measures ANOVA, the within-subject main effects of the three techniques are statistically significant in color A ($F_{2,18} = 14.82$, $p < 0.01$), color D ($F_{2,\,18} = 8.51$, $p < 0.01$), and color E ($F_{2,18} = 6.88$, $p < 0.01$), but not in colors B and C. Post hoc pairwise t-tests using Bonferroni correction show a significant difference between recoloring and luster techniques for color A ($p < 0.001$) and color D ($p < 0.01$). No significant differences are found between recoloring and pattern techniques in colors A, D, E. Overall, ColorBless retains the original color better than the recoloring technique in three of the five colors.

6.4. S4: Subjective Evaluation

Figure 9 shows the average mean values of the rating score given by all 10 colorblind participants. ColorBless was evaluated to be the fastest, takes the least cognitive effort, and is the most obvious in terms of its effect. However, it was also evaluated to be the most uncomfortable among the techniques shown.

In addition, the colorblind participants were asked which technique they preferred in four common use-cases. As shown in Figure 10, in all cases, ColorBless was the most preferred, followed by the PatternBless and pattern techniques. Only two participants preferred the recoloring technique when working alone with graphs.

7. DISCUSSION

In this section, we discuss our findings from the studies and set out to answer the research questions proposed earlier in this article.

7.1. Implementation Guidelines for Binocular Luster in 3D

Concurrent with previous work, our findings show that, given the same brightness differences (dY), the luster effect is more salient and noticeable when the contrast polarity of the left and right image is opposite to each other [Bal et al. 2011]. On

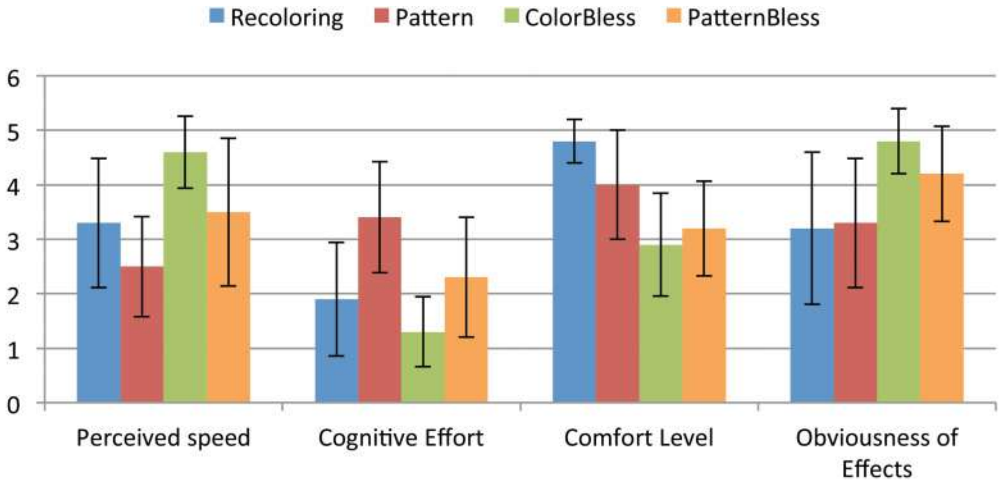

Fig. 9. Subjective evaluation of the colorblind techniques based on four metrics: (a) perceived speed, (b) cognitive effort required, (c) comfort level, (d) obviousness of the effects. Participants rated each using a 5-point Likert scale, and the average mean values for each technique are plotted, with error bars representing standard deviation.

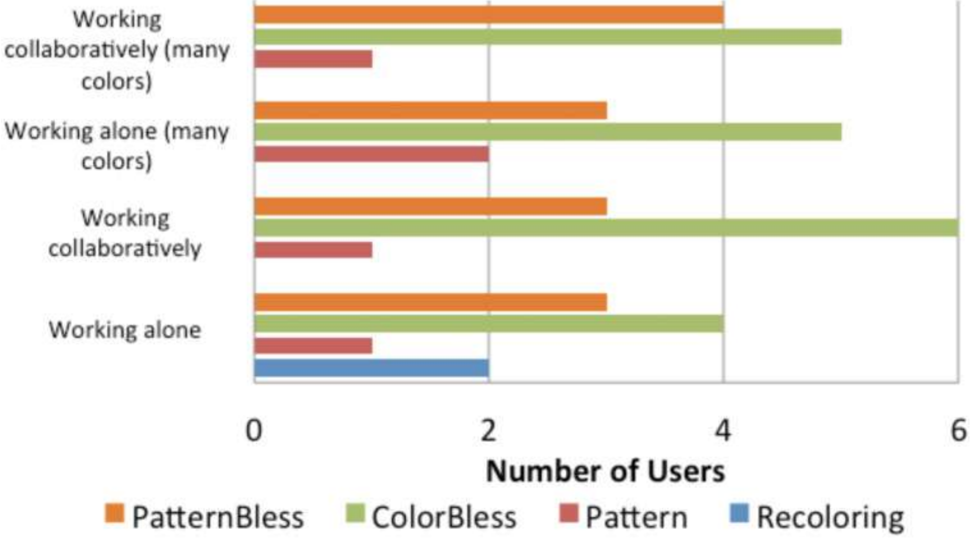

Fig. 10. Colorblind participants' preferences for the four techniques studied in four common use-cases, working with chart images. The number of users who preferred each technique was plotted against different use-cases.

average, a higher luminance difference ($dY = 24$) is needed to perceive a luster effect on stimuli with the same contrast polarity across two eyes, compared to $dY = 13$ on those with opposite polarity. In addition, our findings suggest that contrast polarity is not affected by the hue of the colors in the luster regions. In addition, the difference in colors does not have an effect on the perceptual saliency of the luster effect, at least for the three distinct hues (red, green, and blue) we studied. This suggests that the term "contrast" polarity is only referring to the difference in luminance, not hue.

Table III. Guidelines for Implementing Binocular Luster Effect in Stereo 3D for Images with Same and Opposite Contrast Polarity

	Images with same contrast polarity	Images with opposite contrast polarity
(i) Minimum dY to start perceiving the binocular luster effect	24	13
(ii) Highest dY within the comfortable level	61	44
(iii) Number of distinguishable luster levels between (i) and (ii)	3	3

Conversely, the average comfort threshold dY value for stimuli with same contrast polarity ($dY = 61$) is also statistically significantly higher than stimuli with opposite polarity ($dY = 44$) [Kooi and Toet 2004]. Again, this factor is not affected by hue, and it does not affect the comfort threshold. This points to the interesting observation that, for images with same contrast polarity, although requiring a higher dY value to start perceiving the luster effect, their comfort threshold dYs are also higher. This implies that for images in which a luster effect is applied onto a color and background with same contrast polarity, a higher dY should be used. Between just-noticeable dY and comfort threshold dY, there are, on average, three distinct luster levels at which participants could distinguish the degree of shininess. From our study, contrast polarity and hues do not seem to affect the number of discrete and observable luster levels. Table III outlines the implementation guidelines for applying binocular luster effect in images based on the findings from our study.

7.2. Efficacy of Binocular Luster in Distinguishing Colors

7.2.1. Speed and Clarity. Binocular luster effect was applied in two different ways (ColorBless, PatternBless) to augment the visual information found in images. Our findings suggest that ColorBless is the fastest and most unambiguous in color distinguishing tasks. With ColorBless, the luster effect on top of the confusing colors serves as a form of visual augmentation, like line patterns in the pattern technique. However, due to the straightforwardness and higher saliency of the luster effect, ColorBless allows users to interpret color information more quickly and with lower cognitive effort.

Similarly, with PatternBless our findings suggest that it is also slightly faster and less error-prone than the pattern technique. However, since PatternBless augments color information with patterns rather than using the entire area, it is slightly slower than recoloring and ColorBless techniques due to the additional cognitive effort required to delineate the patterns.

7.2.2. Distinguishing Colors in Small Image Areas. Our findings also suggest that recoloring and pattern technique are not effective (both ER = 0.60) in disambiguating confusing colors in small areas like legends and lines in line graphs. ColorBless, on the other end, is more effective (ER = 0.25). The participants commented that distinguishing colors in small areas is inherently difficult even when a recoloring technique was applied. For the pattern technique, they opined that the line patterns are hard to detect in small color areas, whereas the luster effect does make the small areas easier to distinguish due to its high saliency in binocular vision.

7.2.3. Retaining Original Colors. Color difference-wise, the luster-based technique retains the original color better than the recoloring technique in three of the five colors we tested. Interestingly, for one of the colors for which the luster-based technique failed to show significance in retaining colors (color B), we found that most of the errors colorblind participants made in distinguishing colors with recoloring in study Section S2 were on stimuli using color B. This shows that the recoloring technique is not always effective in enhancing color contrasts and disambiguating colors, as one previous work has shown [Sajadi et al. 2012]. Our findings also suggest that the luster-based technique retains the color slightly better than the pattern technique.

7.3. Subjective Feedback from Colorblind Users

We learned from the post-study questionnaire and interviews that colorblind users place enormous emphasis on reliability and speed when interpreting color-coded information. This is even more important in a collaborative scenario with normal color vision people. Indeed, when asked to rate the importance of speed in distinguishing colors (with a 5-point Likert scale), 8 out of 10 rated it as *very important* when they are alone, and all rated it as *very important* in a collaborative settings.

The findings also suggest that colorblind users generally prefer aids that augment visual information rather than substituting colors. When asked for the rationale behind their preferences, they commented that whereas a recoloring technique could resolve color confusion, colorblind users generally avoid using color hues exclusively due to the anxiety of being wrong.

Earlier, we hypothesized that preference for colorblind techniques is heavily influenced by the cognitive effort required in decoding the color information in an image. Indeed, in the questionnaire, recognizing luster was evaluated as requiring a lower cognitive effort than examining different patterns on different colors, which led to the preference (and faster distinguishing speed) of ColorBless over pattern technique by most colorblind participants.

8. POTENTIAL APPLICATIONS OF BINOCULAR LUSTER BEYOND COLORBLIND AID

In overall, findings from our study suggest that applying a luster effect as a visual cue in a differentiation task is fast and accurate due to its high visual saliency and the low cognitive effort required in the decoding process. The ability to create “invisible” visual elements with a lustrous appearance allows users with 3D glasses to turn their attention to the visuals quickly. From our study, we also discovered that using a luster effect is more effective than using hue for augmenting information in small visual areas.

Beyond highlighting, we see potential applications of the binocular luster effect in augmented visualizations equipped with a stereoscopic setup. The fact that the luster effect could only be seen with 3D glasses without changing the underlying image enables new types of interactions and applications in a collaborative setting where one party requires additional layers of information. For example, in a classroom equipped with a 3D display, students could quiz each other on the learning material by visually augmenting the solution only for students wearing 3D glasses.

Together with our findings that users could differentiate three discrete levels of shininess comfortably, a luster effect could potentially be used to represent ordinal data (with four levels, including the nonluster ones) or even interval data. For example, in visualizing noise level, instead of using a heat map, which obscures and changes the color of the area beneath, a luster effect could be applied to visualize the noise levels of different areas without obscuring the underlying area. In that sense, the ability to create different levels of a luster effect enables the visualization of additional spatial scalar function over an image without obscuring or changing the color and texture of the image.

9. LIMITATIONS

There are several limitations with both luster techniques and the use of binocular luster in augmented visualization in general. First, our techniques require a glass-based

3D-ready setup such as active shutter, passive lenses, and Dolby 3D. Although the implementation we describe in this article is catered for setup using 3D glasses, a luster effect can also be created with nonglass-based stereoscopic displays such as autostereoscopic (albeit under constraining viewing angles and distances) and modern Head-Mounted Displays (HMD) that present a different image to each eye, such as the Oculus Rift Virtual Reality HMD. However, with nonglass-based setups, it is not possible to present original colors to normal color vision people on the same display because only one view can be created with a nonglass setup. With a 3D glass-based setup, however, two different views are possible, with the lustered view presented to users wearing 3D glasses and the nonlustered view presented to users not wearing 3D glasses.

Second, viewing binocular luster effect with a high dY is uncomfortable for the user. Third, our implementation is prototypical and was designed to determine the usability and practicality of luster-based aids. Hence, the algorithms do not handle image background color and background brightness, which could be explored in future work. Fourth, in our study, both luster techniques were tested with only mild and medium deutans participant. Although there are no existing reasons to believe that the applicability of our findings will be affected for severe deutans (as well as for protans and tritans) because the confusion line was derived from the same colorblind simulation algorithm, investigating luster techniques with other types of colorblind people could be a potential work for future researchers.

10. CONCLUSION

In this work, we are interested in the application of binocular luster effect as a colorblind aid. We developed two prototypical colorblind aids, ColorBless and PatternBless, that apply a luster effect with active-shutter 3D in a different manner, and we investigated their effectiveness in augmenting visual information. Through a user study, we validated findings from previous work that binocular contrast polarity is a major factor in the perceived saliency of the luster effect and that participants can differentiate three discrete luster levels comfortably. In addition, our findings suggest that ColorBless is significantly faster and more unambiguous than other techniques, whereas PatternBless trails the recoloring technique slightly in both speed and ER. Colorblind users also preferred luster-based aids to others due to the higher visual saliency and lower cognitive effort involved. Finally, we inferred design implications of applying binocular luster effect from our study and believe it could be potentially used in application domains for augmented visualization.

ELECTRONIC APPENDIX

The electronic appendix for this article can be accessed in the ACM Digital Library.

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