Visibility of Color Breakup Phenomena in Displays Based on Narrowband Spectral Sources

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***Abstract*—The hypothesis that artefacts related to chromatic aberration from eyeglasses may be more objectionable in laser projectors compared to conventional digital projectors was investigated. Untrained observers viewed movie clips in a theater and made image quality ratings. The same four clips were presented on both a standard Xenon display and a prototype laser projector in separate blocks. There was no evidence that observers noticed color break-up artefacts using either mode of presentation.**

***Index Terms*—Aberration, color, display, image quality, laser.**

I. INTRODUCTION

RECENT advanced displays have used spectrally narrowband sources, such as lasers, to generate color images. While this has many advantages, including potentially increasing color gamut and saturation, the use of multiple monochromatic sources might lead to an increased susceptibility to chromatic aberration artefacts. This is because the aberration will separate colors into discrete components (like a line spectrum) rather than the less distinct smear typical with more broadband sources.

A. Chromatic Aberration

The refracting power at a surface is a function of the difference in refractive index of the two media bounded by the surface. The refractive index of a medium in turn varies with the wavelength of light. Therefore the refractive power at the surface is different for different wavelengths (colors) of light. Thus when white light is incident on the surface each wavelength of light is deviated by a different amount and the incident light is separated into color bands. This is known as chromatic aberration and can be considered in two ways. Longitudinal chromatic aberration is the difference in focal lengths of various wavelengths and transverse chromatic aberration is the difference in magnification. Longitudinal chromatic aberration will have the potential effect of reducing the clarity of the image since not all light will be focused at a single point. The color fringes one sees around objects are an effect of transverse chromatic aberration.

Mean dispersion is defined as the refractive index of blue light (480 nm) minus the refractive index of red light (643.8 nm)

$$\text{Dispersion}_{\text{mean}} = n_{480} - n_{643.8}. \tag{1}$$

The dispersive power of a material is equal to the mean dispersion divided by the refractive index of yellow light (587.6) minus one. The V value is the reciprocal of the dispersive power, sometimes referred to as the Abbe number, and is the term commonly used to describe the inherent dispersive properties of a material

$$V = \left(\frac{\text{Dispersion}_{\text{mean}}}{n_{587.6}} - 1\right)^{-1}. \tag{2}$$

Chromatic aberration is inversely related to the V value, and as such the higher the V value the less chromatic aberration. Generally speaking V values are lower for materials with high refractive indices. Currently most spectacle lenses are made with relatively high refractive indices as this reduces lens thickness and improves the appearance of the lenses (refractive indices are commonly in the range of 1.6–1.74 with V-values ranging from 32 to 42). Despite the comparatively low V-values of these lenses, complaints of dispersion are rare in the optical dispensary at the School of Optometry, University of Waterloo, Waterloo, Canada [1].

Chromatic aberration of a prism is equal to the prism power divided by V. Prismatic effect in a lens is equal to the distance from the optical center of the lens in cm times the power of the lens. Therefore, transverse chromatic aberration of a lens is a function of the distance from the optical center, the power of the lens and the V-value of the material. Table I estimates the predicted sensitivity to chromatic abberration for spectacle wearers. The table was generated for various lens powers and viewing angles assuming a 0.1Δ tolerance[1] for transverse chromatic aberration and the lowest V value of the most commonly use ophthalmic materials ([2, p. 368]). Viewing angles are calculated based on a 12-mm vertex distance (distance from back of lens to the eye). The percent of population values are based on mean ocular refraction (MOR) of right eyes from the Waterloo Eye Study (WatES) database. For a description of the database and comparisons to the Canadian population distribution see [3].

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[1] Δ is prism dioptres, 0.1Δ is equivalent to 0.06° of visual angle.

TABLE I
CRITICAL LENS POWER AT VARIOUS VIEWING ANGLES

Distance from optical center (cm)	Viewing Angle (°)	Minimum Lens Power to be Noticeable (D)	% of population with this Lens Power
0.43	20	7.50D	2.7%
0.5	23	6.50D	4.3%
1.0	40	3.25D	18.3%
1.2	45	2.50D	25.4%
1.5	51	2.00D	31.7%

B. Impact in a Cinema Context

In a cinema there is a range of viewing angles dependent on viewer seating position. SMPTE standards [4] for theater design recommend a minimum horizontal field of view of 30° from the rear seats and a 36° field of view is usually assumed for the 'best seats'. In these situations, with the head directed at the center of the screen, horizontal eccentricity will be less than 18°. This value becomes larger for the corners of the screens and for seats closer than optimal. However even in the front row viewing angle will not be extreme as SMPTE recommends a maximum vertical field of view of 35° (horizontal eccentricity is not specified but we assume a horizontal eccentricity of approximately ±30° with a 1.85 aspect ratio).

From the above chart we can estimate the impact of chromatic aberration based on viewing angle and lens power. For a viewing angle of 20° (i.e., approximately the ±18° in the SMPTE standard) it is estimated that a refractive error of about 7.50D would be required for the aberration to become noticeable. About 2.7% of the WatES population requires a spectacle correction of 7.50D or greater (either positive or negative), although many of these will wear contact lenses. The WatES is based on a clinical population as opposed to a general one, resulting in an over-representation of the percentage of persons with refractive errors. Thus the numbers above would represent the 'worst case scenario'. Given that most people start to turn their head rather than their eyes at 15°–20° of eccentricity (see Section II-D), it is very unlikely that more than 5% of the population will notice the chromatic aberration and not all of those will be bothered by it.

C. Objectives

The goals of the present paper are twofold:

1) first, we assess the expected impact of chromatic aberration on the visual comfort and performance of observers in light of the perception and behavioral literature;
2) second, we experimentally assess the visibility and the effects on image quality of spectacle-generated chromatic aberration. The impact of chromatic aberration on image quality in color laser projection displays is difficult to extrapolate from other color break-up phenomena. Unlike field-sequential color displays the effect is static and not dependent on motion. Although the amount of chromatic distortion is identical, the more distinct discrete color fringes may be more salient in laser displays than the equivalent color smear with broadband sources (see Fig. 1). The goal of this study is to assess the visibility and impact of chromatic aberration in these displays.

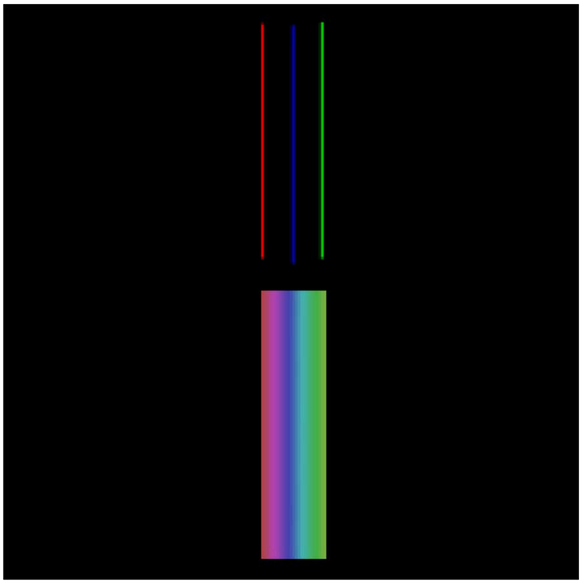

Fig. 1. A schematic illustration of discrete color break-up (upper image) versus color smear (lower image).

Specifically, we ask if observers are sensitive to the color distortion phenomena described above, and if so would it be disruptive enough to degrade the viewing experience? We also ask if viewer sensitivity is affected by the content used.

II. PARAMETERS AFFECTING VISIBILITY OF CHROMATIC ABERRATION PRODUCED COLOR BREAK-UP

A. Adaptation

Wearing a new spectacle prescription is often associated with distortions of space and color due to magnification and aberration of the lenses. Most people rapidly adapt and tolerate their eyeglasses and become less sensitive to these distortions. Ophthalmic lenses induce wavelength dependent prismatic distortion of the images that varies across the lens. A wedge prism placed in front of the eyes produces similar but more uniform effects and hence has been used extensively to study these effects. Gibson [5] found that adaptation to the distorted appearance produced by prismatic effects was slower than typically found for motor adaptation [6]. It has been claimed that adaptation to lens-induced chromatic aberration becomes complete after extended wear although color adaptation appears to be slower than adaptation to curvature distortions (see [6]). Kohler [7] reported that prism-induced color fringes diminished over time and fringes with the opposite color order were produced after ceasing to wear prisms. This after effect has been associated with the McCollough effect [8] and suggests a neural adaptation to optical demands of the prism that diminishes the effects of the chromatic distortion. Presumably, these adaptive mechanisms arose out of the evolutionary need to compensate for the optical distortions of one's own eyes [9] and changes with development and aging. Hay *et al.* [10] found that chromatic adaptation to prismatic chromatic distortions began rapidly in the first two days of exposure plateauing after several days of prism wear. With broad-spectrum illumination and the adapting prism removed, subjects experienced a reverse chromatic aftereffect that could be nulled with an adjustable prism. These post-adaptation fringes were experienced (but could not be nulled) even when testing with monochromatic light, which is consistent with a neural compensation. From their data, Hay *et al.* [10] concluded that the neural mechanism took into account the relative luminance of the target. On the other hand, they found (as did [6], and [7]) that the degree of compensation varied with absolute luminance. Based on this, Held [6] attributed overcompensation to chromatic aberration in his subjects to differences in luminance between the relatively dim laboratory and outdoor daylight environments. In summary, luminance does seem to modestly affect the degree of adaptive response produced with approximately a 2–3-fold difference in compensated dispersion for a 100–1000-fold difference in luminance.

In terms of laser-based displays with well-separated color components, the findings of color fringes for monochromatic light suggests that adaptation is general and should affect the images produced by the laser sources. Adaptation during the viewing itself is unlikely to play a significant role as most viewers will be well adapted to their glasses.

B. Stimulus Parameters

Color and Spectral Purity: As discussed above chromatic aberration results in distortions of position, size and focus that degrade the image. These distortions are wavelength dependent. Increasing separation in wavelength between the color components increases their relative displacement in the image. Thus laser-based displays designed for a large color gamut may be more susceptible to these effects.

In terms of spectral purity, Campbell and Gaubisch [11] showed that chromatic aberration of the eye is in part responsible for the poorer acuity and contrast sensitivity found for white compared to monochromatic light. Spectral components smear and reduce effective resolution and contrast. The effects are much larger on contrast sensitivity than acuity. Additional chromatic aberration from eyeglasses could exacerbate this effect. These contrast effects may be lessened in laser-based displays if the color components break up into well-resolved/spatially separated sub-images rather than a smear of colored light. Interestingly, depth of focus is larger in white light (presumably due to the spectral range).

Luminance: At low luminances the chromatic appearance of the stimulus degrades and disappears as the visual system switches to primarily rod vision. Note that the phenomenon is based on optical segregation of the fringes and hence is expected even when the vividness of color is not apparent. At higher luminances the vividness of the color bars produced should increase. Since typical cinema applications target a screen brightness of 11–17 fL (footlambert), photopic visual acuity and color vision are typically supported, which should promote the resolution and vibrancy of color banding artifacts.

Contrast: Visibility of the color banding effects should increase with relative contrast with the background. Effects on contrast sensitivity were discussed above.

Motion: Unlike the color break-up found in color field sequential techniques, image motion is not expected to play a dominant role although visibility of the phenomenon may be affected (see discussion on eye movements below). Motion blur may act to reduce the visibility of color fringes.

Disparity: Chromatic aberration in the eye gives rise to chromostereopsis which places objects at different disparities depending on their wavelength. This can be exacerbated with additional chromatic aberration from ophthalmic lenses enhancing the illusory depth percept. Thus, with narrow band colored light sources the distinct color bands that arise may appear to lie at different depths.

All of the preceding stimulus parameters will vary depending on the nature of the film content displayed. Fast action sequences will involve more rapid movement of objects in the scene and quick scene cuts, whereas a nature documentary is likely to have slower pacing. Animated cartoon features are more likely to use highly saturated colors and crisp focus. Therefore, it is important that assessment of the presence and effects of chromatic distortions use a range of content sources.

C. Effects of Eye Movements

The role of eye movements in static chromatic aberration-produced color break-up is expected to be distinct from its role in dynamic color break-up in color-field sequential displays. In dynamic color break-up [12], fast saccadic eye movements create high retinal image velocity of displayed features. Due to the color sub-field intervals, the displays of the color components are separated in time causing separation of the sub-field images proportional to eye velocity [13]–[15]. In this case the sub-field images are spatially aligned on the display but not on the retina and these delayed displaced images can be perceptible. Similarly if the object moves on the display, the sub-field delay results in some sub-field images trailing others during the motion [16].

In contrast, with optically produced color break-up, the color components are (or could be) presented simultaneously and spatial offset between the components is static due to the lens aberration. As a result, saccadic eye movements (or rapid image motion) will not change the relative position of color elements. Thus, eye movements are not expected to increase the visibility of the artefacts; in fact the phenomenon of saccadic suppression (e.g., [17]) would likely reduce their visibility. However eye movements play a role by directing gaze. For the typical spectacle wearer the degree of prismatic displacement of the color components will increase with eccentricity or distance from the center of the lens. As the viewer moves their eyes to more eccentric eye orientations (of the eye in the head) the effects should increase as these larger peripheral color separations are viewed foveally and attended to. Therefore, it is expected that static

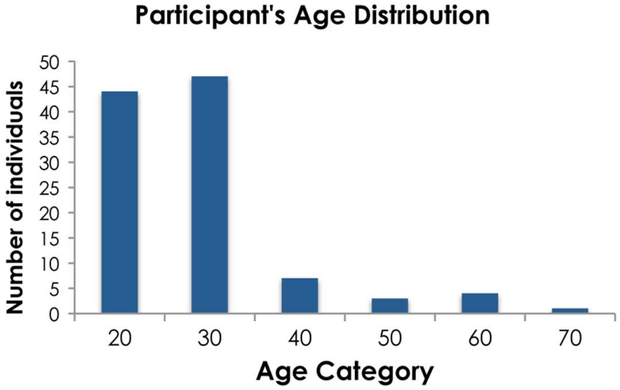

Fig. 2. A histogram depicting the number of participants in each age group in 10 year clusters.

chromatic aberration-produced color break-up is more dependent on static eye position than oculomotor dynamics.

D. Effects of Head Movements

With the head facing straight ahead, looking at peripheral parts of the display by moving the eyes will produce larger color separation and potentially larger perceptual effects. However, if a gaze shift to a peripheral part of display is accomplished by directing the head rather than eyes, the color separation at the gaze target will be minimized. This is because the eye's line of sight will be near the centre of the lens where distortion is minimized. Thus we expect eccentric gaze (or peripheral images) to contribute to the visibility of the artefacts but only when accomplished with large eye deviations. To our knowledge, the relative contribution of eye and head movements to gaze movements in a cinema setting has not been studied. In laboratory settings large eye eccentricities (position of the eye in head) are rare; people tend to move their eyes for small gaze changes but move their head as well for eccentricities greater than ±20°. Barnes [18] found that when subjects made a typical unrestrained gaze change, the head movement accounted for 80% of the movement. Similarly Gresty [19] found that for target movements larger than 15° head movement accounted for approximately 80% of the gaze shift. This is true even for very large eccentric gaze movements beyond the eye movement range although during the gaze shift the eye may transiently make larger movements [20]. In a cinema setting one might expect somewhat less head movement due to the static stationary seated posture but this is conjecture.

III. EVALUATION

A. Methods

Naíve observers with low to high myopia (wearing glasses, not contact lenses) were recruited from the University of Waterloo. A total of 105 observers participated; 57 of these were female. The majority of these were students ranging in age from 17–25 years, however, an effort was made to also recruit some older observers (30 years and above). See Fig. 2 for a histogram depicting the distribution of ages tested.

TABLE II
PROJECTOR PROPERTIES

Parameter	**Laser Proto1**	**Christie CP2000**
Illumination	Laser	Xenon Lamp
Resolution (Projector)	2048 x 1080	2048 x 1080
Resolution (Content)	1280 x 720	1280 x 720
Frame Rate (Content)	24 Hz	24 Hz
Convergence	within theatrical specs	within theatrical specs
Brightness	45.5±1.0 cd/m^2	45.5±1.0 cd/m^2
Spectral Bandwidth	465±5, 532±5 and 639±5 nm	456±28nm, 540±32nm, and 642±38nm

All testing took place in a local theater which could simultaneously accommodate two projectors. See Fig. 3 for a schematic diagram of the theater setup. A prototype laser projector (Laser Proto1) installed by Christie was compared with a Christie CP2000 Xenon projector (see Table II). The two projectors were placed side-by-side in the projection booth, adjusted for 13 fL (45.6 cd/m^2) on the screen and set to identical DCI color settings. The high-gain silver screen was 49.5′ (15.1 m) wide and was a top-masking (or constant width) type of installation. The theatre was a conventional configuration with stadium-style seating. Convergence for both projectors was verified to be within theatrical specifications.

During bus transportation to the cinema, subjects completed the informed consent form and demographic questionnaire and were given a brief description of the goal of the study.

Upon arrival at the cinema, participants assessed their visual acuity using a Snellen Letter chart. They were asked to record on their response form the smallest line of letters that they were able to reliably read while wearing their optical correction. Four charts were set up in the lobby of the cinema, with a viewing distance of 10′ (3.05 m) marked in tape on the floor. On average, participants could successfully read the 20:20 equivalent line on the Snellen chart (with a standard deviation of 1 line). Thus on average, our participants had 20/20 vision while wearing their prescribed correction. See Figs. 4 and 5 for details on acuity and length of time wearing eyeglasses, respectively. Reported spectacle prescription covered a wide range consistent with expectations with a normal spectacle wearing population.

Following acuity testing, participants were ushered into the theater and asked to sit in a seat with a pre-assigned number. Prior to testing every 2nd seat had been numbered. Once seated, participants used their seat number as an identifier on all data response sheets.

One of the Experimenters stood at the front of the theater and, prior to testing, summarized the procedure and addressed any questions. During testing, following each clip he told the participants which response form to fill out, and gave final instructions when the testing was completed.

Data was collected over two days and on each day we collected responses in two blocks, one for each projector (Laser and Xenon). Each of the two blocks in a test session consisted of viewing a set of four short (3-min) clips:

1) cartoon
2) color film with subtitles;
3) black and white footage (no subtitles);
4) color film without subtitles.

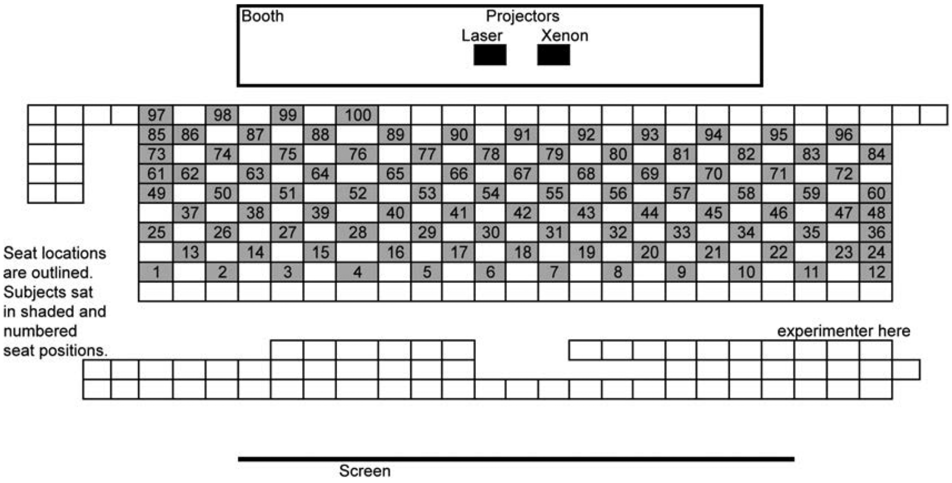

Fig. 3. A schematic (not to scale) of the layout of the theatre used for the experiment.

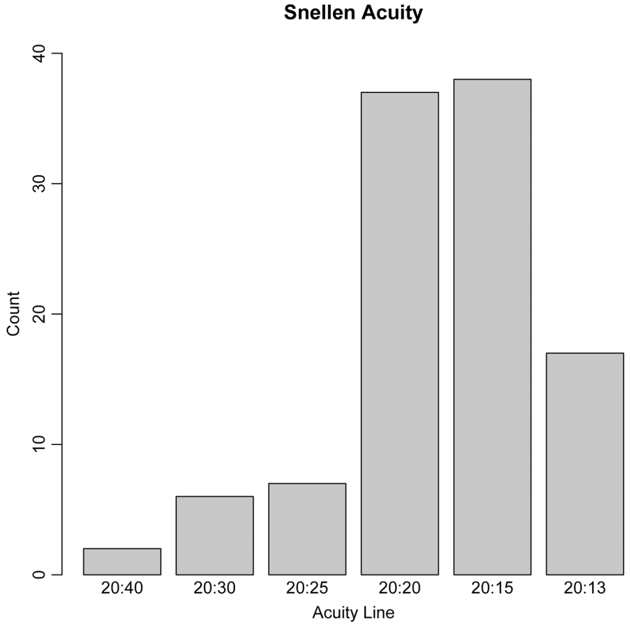

Fig. 4. Snellen acuity (binocular) of the observers.

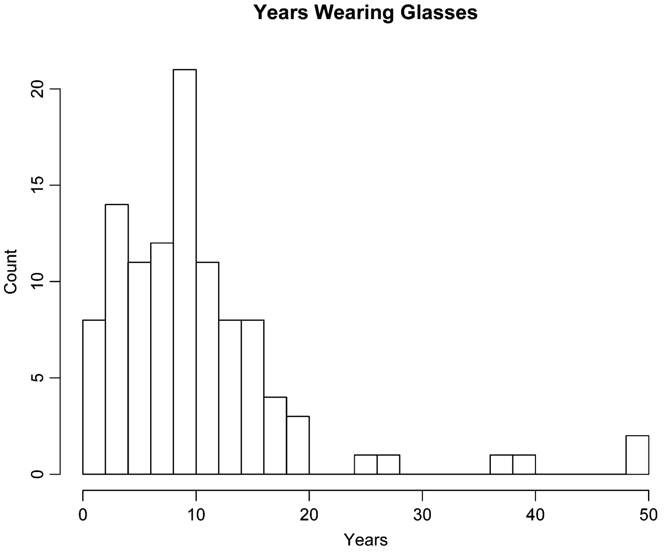

Fig. 5. Histogram depicting the length of time (in years) wearing glasses for participants.

Following each 3-min clip, observers were asked to complete a response form, which asked them to rate a number of attributes on an 8-point scale (0–7), and to comment on any unusual phenomena (Table III). The sequence of clips was completed in the same order twice, once per projector. At the end of the test session participants were asked to indicate which projection technology they preferred (though they were not aware of the type of projector used in each block of trials), and why. On the second day, projector order and the order of the clips were reversed to control for effects of the test sequence.

Categorical data were collected for all variables, therefore medians and quartiles were determined rather than means and standard deviations. Chi-Square tests based on the Wilson score intervals were used to test for differences in proportions of responses for binomial data [21]. For tests with cells that had expected frequency of less than 5, continuity corrections were performed. Ranked Sign Tests were used for variables measured with 8-point scales. A probability of <0.05 was used as the criterion for statistical significance.

B. Results

Questionnaire data was transcribed into a spreadsheet and preliminary comparisons were made to ensure that the two data sets (day 1 and day 2) were comparable.

The primary objective of this study was to determine if "typical observers" would be sensitive to chromatic aberration caused by viewing laser projection imagery while wearing corrective lenses. To assess this we evaluated all responses to the question: "Did you notice any unusual phenomenon such as glare/fading color/jerky images/multiple images?". The percentage of responses to this question involving some comment related to color is shown in Fig. 6. We counted the number of references to color-based phenomena, including glare and overall color shifts for each projector type. The percentage of participants who commented on any color-related

TABLE III
QUESTIONNAIRE QUESTIONS (MAINLY LIKERT SCALES USING CHECK BOXES). QUESTION 5 WAS ONLY INCLUDED WITH THE SUBTITLED CLIP

Question	Range
1. How comfortable was your visual experience while watching the movie /clip	Not comfortable = 0, Very comfortable = 7
2. How would you rate of the clarity of the movie/clip	Not clear = 0, Very clear = 7
3. How would you rate the overall brightness of the movie/clip	Too Dim Acceptable Too bright
4. How would you rate the quality of the colors/ gray levels in the movie/clip	Very poor quality = 0, Very good quality = 7
5. How would you rate the difficulty in reading text (subtitles/credits) in the movie/clip?	Very difficult = 0, No difficulty = 7
6. Did you notice any unusual phenomenon such as glare/ fading color/ jerky images/ multiple images?	Please describe
6a. If you answered YES, please indicate where you saw the phenomenon. Choose as many options as are relevant. While looking:	Straight ahead, Sideways, Up, Down, Other
6b. Did you find this bothersome?	YES NO
7. Did you notice any sparkles or speckles?	YES NO
7a. If you answered YES, please indicate where you saw the sparkles or speckles. Choose as many options as are relevant. While looking:	Straight ahead, Sideways, Up, Down, Other
7b. Did you find this bothersome?	YES NO

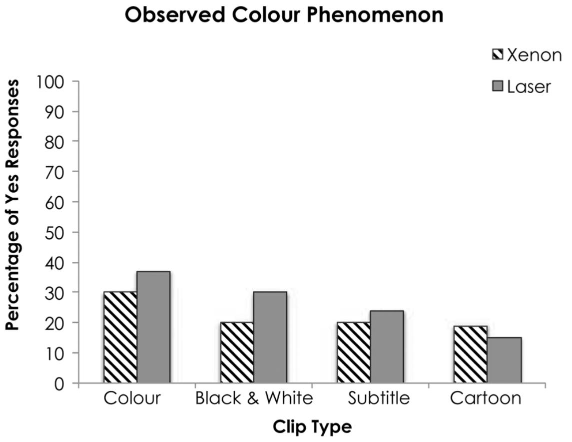

Fig. 6. Percentage of "Yes' responses when participants were asked whether any unusual color phenomena were observed for each of the four clip types. There was a trend for unusual color phenomena to be reported more frequently with the laser projector for the black and white clip only but this effect did not reach significance $(\chi^2(1) = 3.5897, p = 0.058)$.

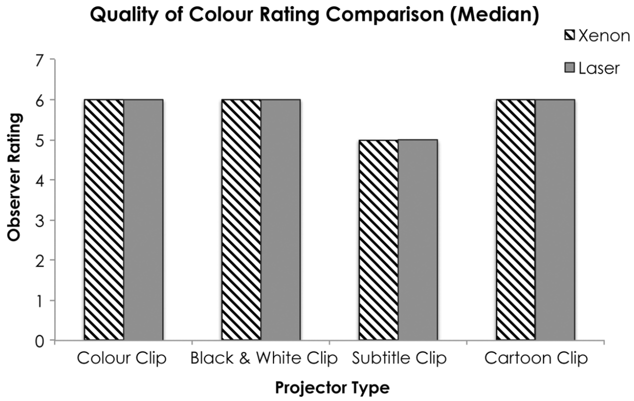

Fig. 7. Graph depicting the participants' ratings of the four different clip types based on color quality. The ratings were identical for the two projectors across all clip types.

phenomenon on any clip in the two projector conditions were not significantly different ($\text{laser} = 13/105$, $\text{xenon} = 11/105$).

Note that examination of the comments showed that none of the observers reported color banding or multiple color phenomena. All of the instances documented are related to "glare"' or overall color shifts (e.g., "yellower colors"). Similarly there was no difference in the subjects' ratings of color quality (or contrast for the black and white clip) between the two projectors (Fig. 7).

Ease of reading subtitles was of particular interest since these high contrast features might be expected to exhibit more break-up artefacts. However, there were no differences in the ratings for ease of reading subtitles in the two projected displays and the median response for both was "No Difficulty."

In addition to our primary objectives, in the questionnaire, we included questions regarding the relative comfort, clarity, brightness, and presence of speckle or sparkle for the two types of projector. The median ratings on all of these questions were virtually identical (in most cases they were identical). Statistically there were no significant differences between the two projectors except for the following. For the color clip there was a significant difference between the two projectors for comfort and clarity (Ranked Sign test $Z = 3.28$, $p = 0.001$ for comfort, and $Z = 2.60, p = 0.009$ for clarity). In both instances the median values were the same for both projectors but the values that were below the median were lower for the laser projector giving rise to the statistical difference. Speckle was reported statistically significantly more frequently with the laser projector but only for the clip with subtitles $(\chi^2(1) = 4.70, p = 0.030)$ as can be seen in Fig. 8. This finding might be spurious. The fact that speckle was reported at all for the Xenon projector suggest that participants could not distinguish speckle from other artifacts. In particular it is important to note that the screen was a high-gain silver screen which is expected to give rise to sparkle artifacts; it may have been sparkle that the subjects responded to in either the Xenon or both the Xenon and Laser cases. As we did for color-based comments, we assessed all responses for

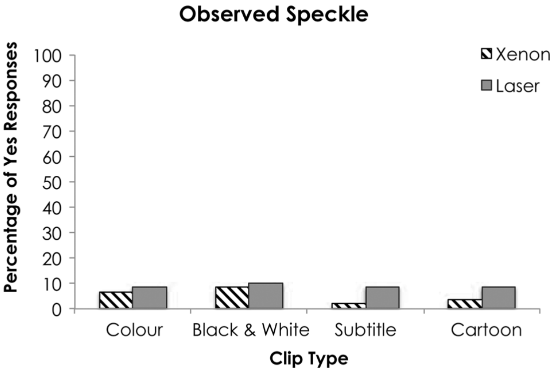

Fig. 8. Percentage of "Yes" responses when participants were asked "Did you notice any sparkles or speckles?" for each of the four clip types.

those that were speckle-related in both projector conditions in terms of the percentage of participants who commented on any speckle/sparkle phenomenon in the two projector conditions. The numbers were identical for the two projectors (15/105, a single observer was counted only once for each projector type if they made any negative comments on any clip for that projector).

IV. CONCLUSION

Analysis of the problem of chromatic aberration produced color break-up suggested that relatively few if any observers would be expected to notice or be bothered by the effect. Consistent with this analysis, reports from naive observers wearing optical correction showed that they were not aware of color banding or separation effects when viewing either traditional xenon lamp or a prototype laser projector. Any observed color effects were the same for the two projectors. Importantly there were no reports of color break-up or color banding. The lack of sensitivity to these phenomena suggest that the laser projection technology is not distinguishable from xenon projection in these respects, when the two are viewed sequentially (rather than side-by-side). This is also the case for the relative comfort, clarity, brightness, color quality and ease of reading subtitles.

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