Sequential color breakup measured with induced saccades

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ABSTRACT

The commercial success of color sequential displays is limited by the fact that people perceive multiple color images during pursuit and saccadic eye movements. We conducted a psychophysical experiment to quantify visibility of these color artifacts for different saccadic speeds, display background brightness, and target size. An Infocus sequential-color projector was placed behind a projection screen to simulate a normal desktop display. Saccadic eye movements were induced by requiring subjects to recognize text targets displayed at two different screen locations in rapid succession. The speed of saccadic movements was varied by manipulating the distance between the two target locations. A white bar, either with or without a yellow and red color fringe on the right edge, was displayed as subjects moved their eyes for the text recognition task. The two versions of the white bar will not be distinguishable if color break-up is present, thus performance of this task can be used as a measure of color break-up. The visibility of sequential color breakup decreases with background intensity and size of the white target, and increases with saccadic speed.

Keywords: color breakup, sequential color, saccade, visual perception

1. INTRODUCTION

Sequential color displays produce color images by displaying the color components (usually Red, Green, and Blue, or RGB) sequentially in time, and rely on the observer's eyes to merge the individual RGB images into a full color image. When an observer's eyes move rapidly relative to the display screen, the R,G, and B images will not fall on the same location on the retina. This can result in color breakup, or perceived spatial separation of the R,G,B components.

The severity of the color breakup effect has been found to be a function of target luminance, luminance modulation, retinal velocity, and the spatial configuration of the target.[1–3] Most of the earlier experiments on color breakup were done with passive retinal motion, i.e. the subjects' eyes fixated at one point while the stimuli moved.[1,2] While these earlier results provided valuable insight into color breakup thresholds and variables that affect them, they may have over-estimated the level of color breakup given a particular retinal velocity, since in these experiments retinal motion was not caused by active saccades.

During an active saccade, the spatial and spectral sensitivity of the eye is temporarily reduced.[4] This phenomenon is called saccadic suppression. Perceptual artifacts such as color breakup may become less perceptible in the presence of saccadic suppression. We conducted a psychophysical experiment to measure the perceived level of color breakup caused by induced saccadic eye movements.

2. EXPERIMENT

A dual-task experiment was designed for this study. One task was used to induce saccadic eye movements, and the other task was used to measure the level of perceived color breakup.

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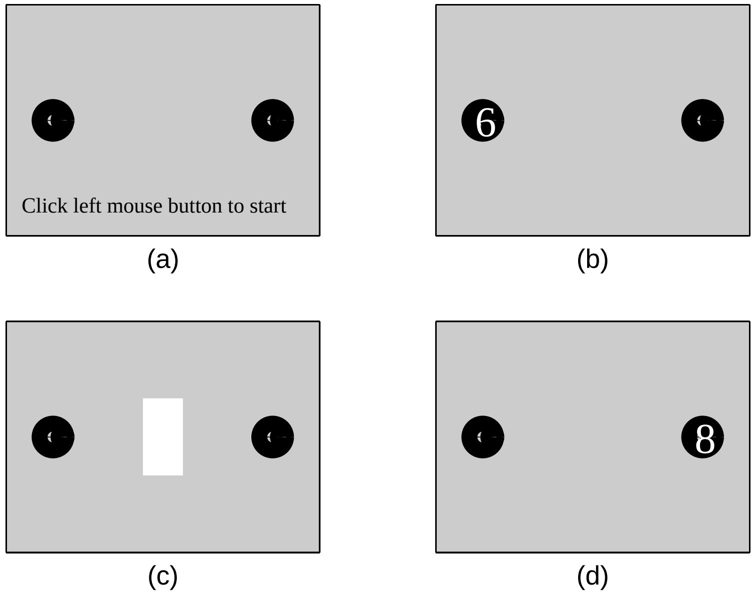

Figure 1. Sequence of screen configurations for the saccade task. This is an illustration only – distances and sizes of objects on screen are not in correct proportions.

2.1. Saccade task

Saccadic eye movements were induced by requiring subjects to recognize text targets displayed at two different screen locations in rapid succession. The text targets are single-digit numbers (0-9). For each trial, the first number symbol appears in the left text field for 50ms, then disappears, and after an interval of 83ms, a second number symbol appears on the right text field for 50ms. An on-screen numeric keyboard then appears so that subjects can click in the two numbers they saw using a mouse pointer. An illustration of the sequence of screen configurations for this task is shown in Figure 1. Since text recognition is a task that requires foveal vision, subjects needed to fixate on the first text location initially, then after recognizing the first number symbol, rapidly saccade to the second text location. Therefore, success in performing this task is a good indicator that a saccade occurred during the time interval between the two text presentations.

Saccade amplitude was controlled by varying the on-screen distance of the two text presentation locations. We used 2 distances in the experiment, 10 and 18 degrees of visual angles. Since both peak velocity and mean velocity of a typical saccade increases with saccade amplitude,[5,6] we could vary the retinal velocity of stimuli on the saccadic path by using the two different saccade distances in our experiment.

A typical saccade of 18 degrees visual angle takes 60-80ms to complete.[6,7] Hence, we chose an inter-stimulus duration of 83ms. This interval was brief enough to encourage a saccade, yet long enough for the task to be accomplished.

2.2. Sequential color task

Sequential color breakup was measured by a color detection task. During the saccadic eye movement induced by the text recognition task, a white bar was displayed at the mid-point of the saccade path (Figure 1c). The height of the bar was 15.6 degrees visual angle. Its width was set at 1, 2, or 4 degrees of visual angle. The luminance of the bar was 85 cd/m^2. In half of the trials, the white bar was just a white rectangle (Figure 2a). In the other half of the trials, a yellow and red color edge was created on the right hand side of the white bar by adding 2 extra vertical lines of red pixels and omitting 2 vertical lines of blue pixels (Figure 2b). The combined yellow and red color edge was 0.25 degrees of visual angle in width. The color edge was easy to detect in the absence of sequential color breakup. If color breakup

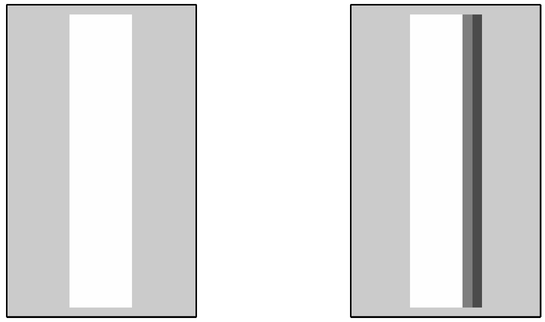

Figure 2. Illustration of the white bar, with or without a yellow and red color edge, used in the sequential color task. The bars are not drawn to proportion. The color edges are shown in grayscale here, and are widened for easier viewing.

happens during a saccade, however, the R, G, and B color planes will be separated in space, and the difference between a white bar with or without a color edge should be very difficult to detect. Therefore, the performance of this task can be used as an indicator of perceived color breakup.

2.3. Apparatus

Most of the data collection was done on a simulated desktop display, which consisted of an InFocus sequential-color projector placed behind a projection screen. The whole setup was housed in a plastic enclosure to resemble a normal desktop display. The InFocus projector was run at 120Hz frame rate, with 3 sections on the color wheel (red, green, and blue), giving a field rate of 360Hz. The resolution measured at the screen surface was 52dpi. The maximum luminance of this display was about 85 cd/m^2. Color display calibration measurements[8] were used to calculate proper pixel values for the experimental stimuli. During the experiment, subjects sat at a viewing distance of 18 inches from the surface of the screen.

One of the subjects also completed a control experiment using a CRT display. The CRT display was similarly calibrated, and stimuli were generated to have the same colorimetric values as those on the projector display. Viewing distance was adjusted so that the effective stimulus size (in visual angles) was the same as on the projection display. The CRT display was run at 60Hz, so that stimulus presentation times can be easily matched to the projector version.

2.4. Design and subjects

Three independent variables were included in the experimental design, which gave a total of 18 unique combinations of the independent variable levels, or 18 conditions, in the experiment.

1. Saccade amplitude (distance): 10 and 18 degrees visual angle (corresponding to 160 and 288 pixels between the centers of the two text presentation locations on the display we used). This is designed to investigate the relationship between retinal velocity of the target and the severity of color breakup in the presence of saccadic suppression.

2. Background luminance level: 1, 4, and 15 cd/m^2. This variable is included in the experiment to determine whether color breakup can be alleviated or masked when the background is not completely dark.

3. Width of the white bar used in the sequential color task: 1, 2, and 4 degrees of visual angle (corresponding to 16, 32, and 64 pixels). We varied the size of the white bar in order to determine whether local luminance levels also affects the visibility of the color breakup artifact.

Three subjects participated in the experiment. Two were the authors, and one was a volunteer. All subjects had normal color vision as tested by the Ishihara plates.[9] Each subject completed 6 sessions of the experiment on the projection display, and each session included 144 trials (8 trials per condition), randomized in their order of presentation. One subject also completed 6 sessions on the CRT display. Since performance of the sequential color task was near perfect on the CRT regardless of the independent variable settings, no more data were collected in the CRT experiment.

2.5. Procedures

Each trial of the experiment started with a screen showing the 2 text fields for the text recognition task, as illustrated in Figure 1. The text fields were two blue discs with diameters of 1.25 degrees visual angle (Figure 1a). A green text message on the screen informed the subject to click a mouse button to initiate a trial when ready. This allowed the subject to prepare his/her gaze and saccade. When a mouse button was pressed, a randomly chosen single digit number was flashed on top of the left blue disc for 50ms (6 vertical refresh intervals on the projector display, and 3 on the CRT)(Figure 1b). The number symbol was displayed in red. Then the red number symbol disappeared, and the white bar stimulus for the sequential color task was flashed on at the center of the screen for 83ms (10 vertical refresh intervals on the projector display, and 5 on the CRT)(Figure 1c), and then disappeared. Another randomly chosen single digit number, also displayed in red, was then presented on top of the right blue disc for 50ms before it disappeared (Figure 1d). After the stimulus presentation, an on-screen numeric keypad became visible, and subjects were asked to click on the two single digit numbers in the order they saw them. Finally, they were asked to click the left or right mouse button to indicate whether or not they saw a color edge on the white bar during their saccade from the left text location to the right text location. Feedback was given for the sequential color task at the end of the trial.

Apart from the white bar used in the sequential color task, all other on-screen objects were displayed in one of the 3 primary colors (red, green, or blue). Therefore, nothing else on screen could cause color breakup to distract the subjects from the sequential color task.

3. RESULTS AND DISCUSSIONS

Subjects' responses to both tasks were recorded. Performance of the saccade task (text recognition) indicated subjects did in fact make saccadic eye movements between the first and second text fields. Overall accuracy of the saccade task was uniformly high, varying from 96% to 99% among the three subjects. A 3-way ANOVA performed on the accuracy percentages for each condition showed no significant effect of background luminance ($p > 0.15$), target width ($p > 0.99$), and saccade distance ($p > 0.58$). This confirms that for all experimental conditions, the subjects moved their eyes between the two text presentation locations in order to successfully perform the text recognition task.

Performance of the sequential color task is calculated only on trials for which the saccade task was correctly performed. Out of the 2592 total trials performed by the 3 subjects on the sequential color projection display, 61 trials were thrown out due to incorrect responses in the text recognition task. The rest were used to calculate percentage correct responses for the sequential color task.

Figure 3 shows the percent correct detection for the sequential color task separately for the 3 subjects. Overall, the effect of color breakup increases with saccade distance, decreases with background luminance level, and decreases with target width. A 3-way ANOVA applied to the percentage correct responses revealed significant effects of saccade distance ($p < 0.005$), background luminance ($p < 0.0001$), and stimulus width ($p < 0.05$). No significant interactions were found among the independent variables. There is qualitative agreement among the subjects, hence the three subjects' data are combined in all future analyses.

Figure 4 plots the performance of the sequential color task when all subjects' data are combined. It is easy to see the effect of the individual variables on the severity of sequential color breakup experienced by the subjects.

Performance of the sequential color task on the CRT display by subject M was near perfect for all conditions, and did not vary with the independent variables. This confirmed that the sequential color task was easy to perform on a non-field-sequential display, and performance degradation on the projection display was likely due to interference from perceived color breakup.

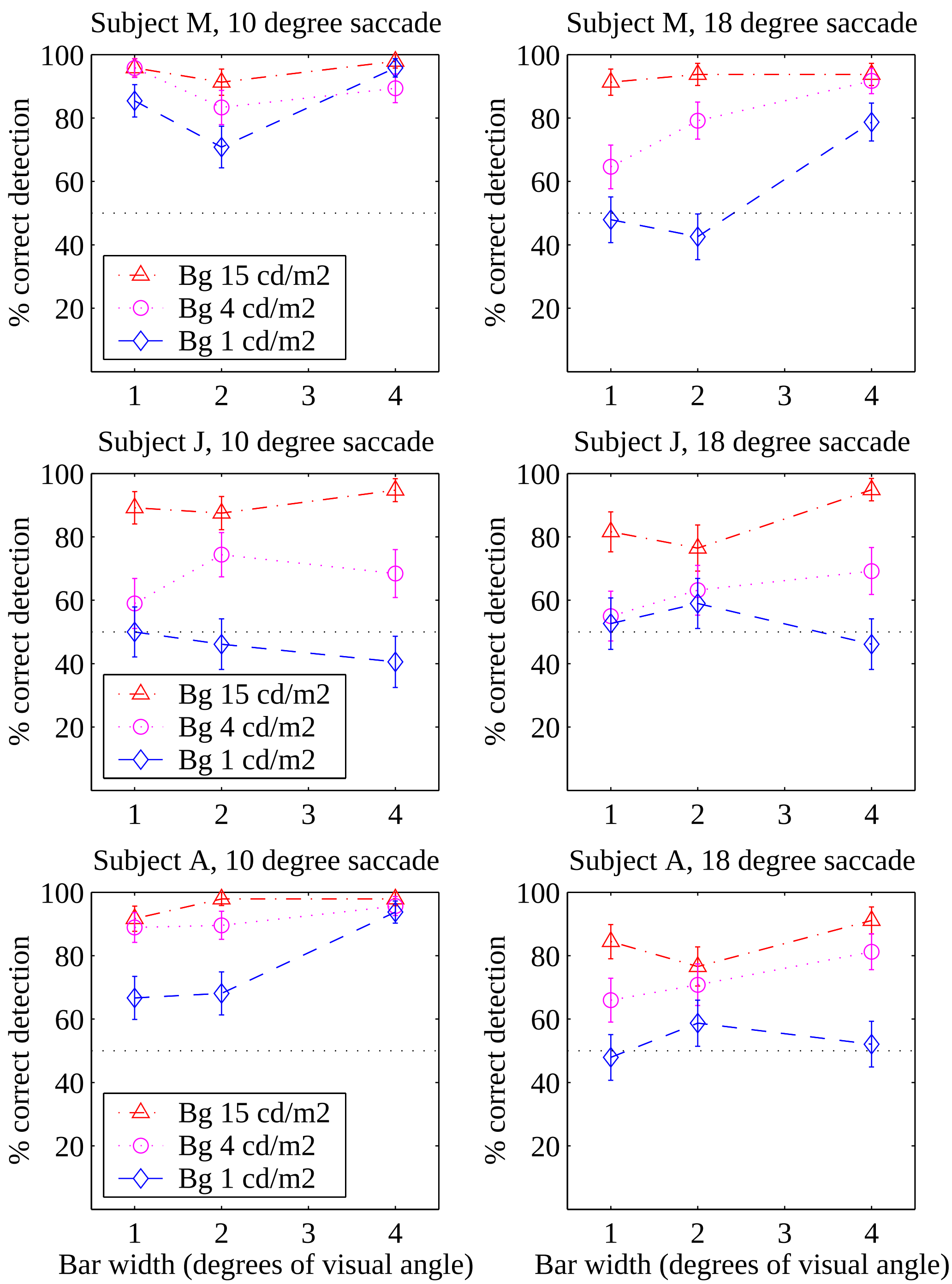

Figure 3. Percent correct detection for the sequential color task as a function of stimulus bar width, plotted separately for different background luminance levels, saccade distances, and subjects. Lowest level performance (50%, marked as dotted horizontal line in the plots) indicates presence of strong color breakup, while perfect (100%) performance suggested minimal effect of color breakup.

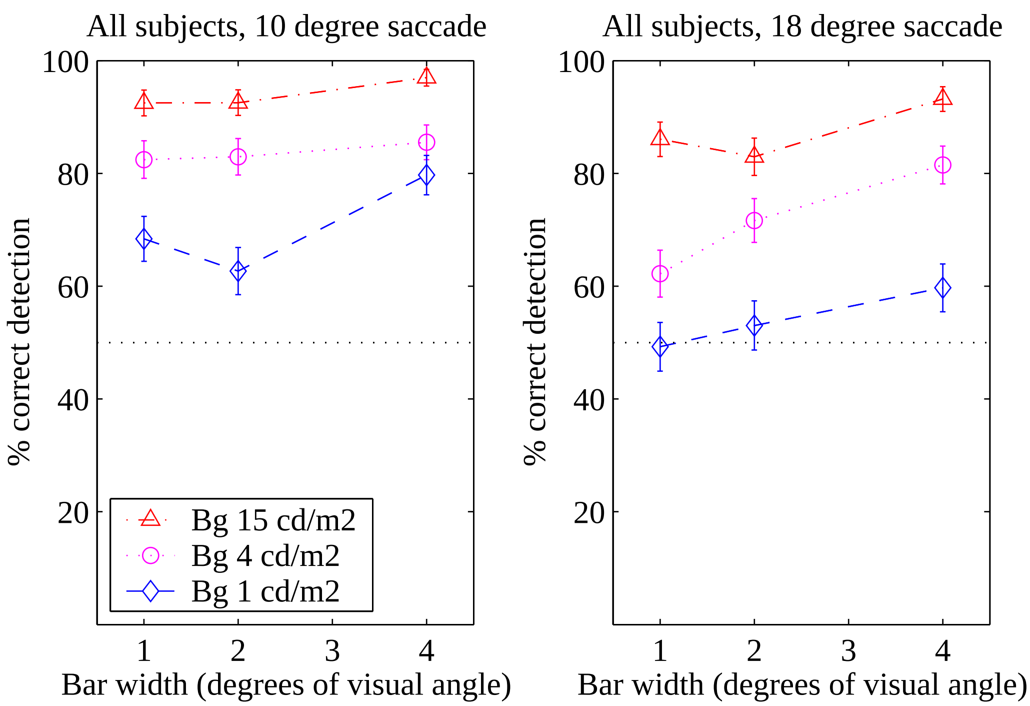

Figure 4. Percent correct detection for the sequential color task as a function of target width, background luminance, and saccade distance. All 3 subjects' data are lumped together for these plots.

Post et al[1,2] measured color break-up thresholds with moving stimuli, and derived an empirical equation to predict color breakup given target luminance, target luminance modulation, and retinal velocity. In their experiments, color breakup was induced by moving targets instead of subjects' saccades. It is interesting to compare the results with the present study. We calculated predicted threshold field rates using the equations given in Post's papers (both the 1997 and 1998 ones). The threshold field rate is the frame rate (Hz) below which color breakup is perceived. Following Post's convention, we use L to denote target luminance level, M to denote target luminance modulation relative to the background, and V to denote retinal velocity. We determine the L, M, and V values for our data as follows:

1. Target luminance $L = 85$ cd/m^2. This value was fixed in our experiment.
2. Target luminance modulation $M = (L - L_b)/(L + L_b)$, where L_b is background luminance in cd/m^2. This is calculated the same way as described in Post's papers.[1,2]
3. Retinal velocity V: We use peak retinal velocity estimates of 300 and 500 degrees per second for the 10 and 18 degree saccades.[6,7]

Post et al gave two different equations to calculate threshold field rate in the 1997 and 1998 papers. They were fitted to empirical data using slightly different stimulus configurations. The setup and design of our experiment were quite different from both of Post et al's experiments, so we calculated field rates using both equations for the sake of completeness.

Threshold field rates are calculated for the 3 background levels and 2 saccade distances used in our experiment, to yield a total of 6 comparison points. We compare these results to the color breakup measurements (% correct in sequential color task) for the smallest target size (1 degree visual angle in width) in our experiment, as the stimuli used

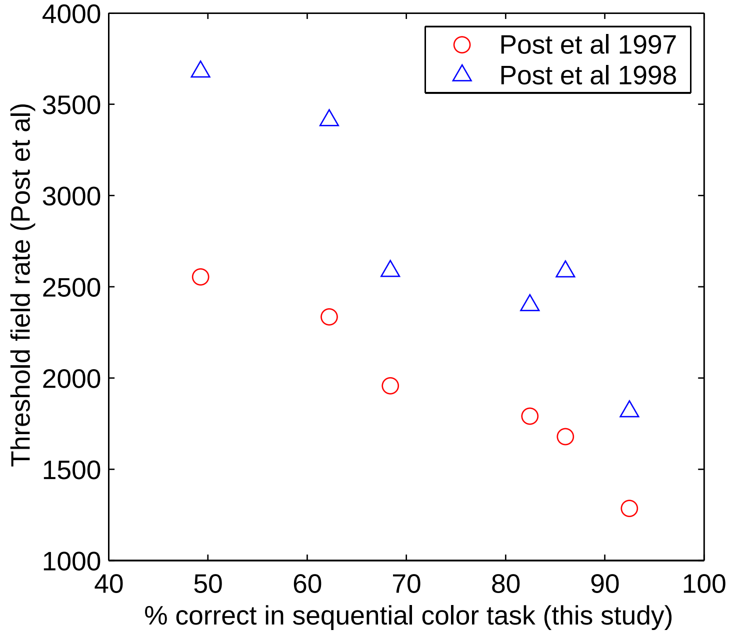

Figure 5. Comparison of predicted threshold field rates and sequential color task performance from our experiment.

in Post et al's studies were much smaller in size. The comparison is shown in Figure 5, where predicted threshold field rates are plotted against percentage correct in the sequential color task.

Our measured color breakup levels, which were mostly supra-threshold, are qualitatively consistent with threshold field rates calculated from Post's data. As color breakup becomes easier to see, threshold field rate needs to be higher, while performance for the sequential color task should be poorer. The plots in Figure 5 indeed show a negative correlation between predicted threshold field rates and performance in our sequential color task.

All the threshold field rates plotted in Figure 5 are well above 1000Hz, higher than the 360Hz field rate of the display used in our experiment. This difference might be a result of the many differences in the stimulus and setup of the two experiments. In Post et al's studies target size was much smaller than the target in the present experiment, thus color breakup was much easier to see, resulting in high threshold field rates. Another possibility is that saccadic suppression during active saccades reduced the visibility of color breakup in our experiment. The cause of this difference can not be conclusively determined without further experiments.

4. CONCLUSIONS

We conducted a psychophysical experiment to study color breakup artifacts for a sequential color display using induced saccades. Results showed that peak retinal velocity, background luminance level, and target size all have significant effects on perceived color breakup. Our results are qualitatively in agreement with previous studies using moving stimuli and fixed viewing.[1]

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REFERENCES

1. D. L. Post, "Predicting color breakup on field sequential displays: Part 2," in *Society for Information Display Symposium Technical Digest*, pp. 1037–1040, SID, 1998.
2. D. L. Post, P. Monnier, and C. S. Calhoun, "Predicting color breakup on field sequential displays," in *Proceedings of the SPIE: Head-Mounted Dispalys II*, **3058**, pp. 57–65, SPIE, 1997.
3. J. B. Eichenlaub and J. M. Hutchins, "An improved field-sequential-color technique for lcds," in *Proceedings of the SPIE: Liquid Crystal Materials, Devices, and Applications III*, **2175**, pp. 132–142, SPIE, 1994.
4. K. Uchikawa and M. Sato, "Saccadic suppression of achromatic and chromatic responses measured by increment-threshold spectral sensitivity," *Journal of the Optical Society of America A* **12**(4), pp. 661–666, 1995.
5. W. Becker, *Metrics*, pp. 13–67. Elsevier, Amsterdam, 1989.
6. A. T. Bahill, M. R. Clark, and L. Stark, "The main sequence, a tool for studying human eye movements," *Mathematical Bioscience* **24**, pp. 191–204, 1975.
7. M. R. Harwood, L. E. Mezey, and C. M. Harris, "The spectral main sequence of human saccades," *The Journal of Neuroscience* **19**, pp. 9098–9106, Oct. 1999.
8. D. H. Brainard, "Calibration of a computer controlled color monitor," *Color Research and Application* **14**, pp. 23–34, 1989.
9. S. Ishihara, *Tests for Colour-Blindness*, Kanehara Shuppen Company, Ltd., Tokyo, 1977.