On Spatiochromatic Visual Sensitivity and Peripheral Color LOD Management

ANDREW T. DUCHOWSKI and DAVID BATE
School of Computing
and
PARIS STRINGFELLOW, KAVERI THAKUR, BRIAN J. MELLOY, and ANAND K. GRAMOPADHYE
Industrial Engineering
Clemson University

Empirical findings from a gaze-contingent color degradation study report the effects of artificial reduction of the human visual system's sensitivity to peripheral chromaticity on visual search performance. To our knowledge, this is the first such investigation of peripheral color reduction. For unimpeded performance, results suggest that, unlike spatiotemporal content, peripheral chromaticity cannot be reduced within the central 20° visual angle. Somewhat analogous to dark adaptation, reduction of peripheral color tends to simulate scotopic viewing conditions. This holds significant implications for chromatic Level Of Detail management. Specifically, while peripheral spatiotemporal detail can be attenuated without affecting visual search, often dramatically (e.g., spatial detail can be so reduced up to 50% at about 5°), peripheral chromatic reduction is likely to be noticed much sooner. Therefore, color LOD reduction (e.g., via compression), should be maintained isotropically across the central 20° visual field.

1. INTRODUCTION

Human color perception stimulates synthetic color image creation, compression, and reconstitution. Perceptually based light reflection models have been devised [Pellacini et al. 2000], as have algorithms
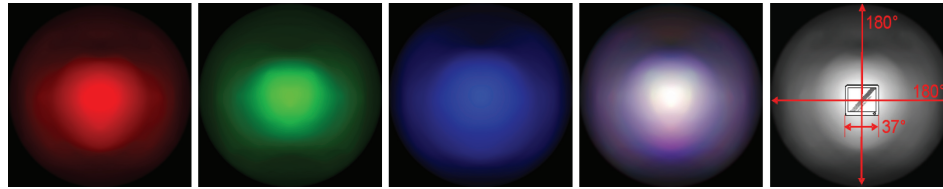

Fig. 1. Peripheral color degradation maps: R, G, B channels and the trichromatic map, lef to right resp., covering the entire 180° × 180° field of view, based on symmetrically mirrored color zone maps obtained psychophysically by Sakurai et al. [2003] (see Figure 2)—note the parafoveal sensitivity to blue extending beyond the approx. 10° conjectured by Wyszecki and Stiles [1982]. For an indication of scale, an illustration of a 17″ flat panel monitor (far right) is superimposed subtending a 47° (diagonal) viewing area (approx. 37° × 30°) at 50 cm viewing distance.

for image and video compression [Komogortsev and Khan 2004], and correction of perceptual color deficiencies through recoloring [Rasche et al. 2005]. Unless explicitly stipulated, however, perceptually-based image synthesis tends to assume color as perceived by the fovea. Peripheral vision is dramatically different. Of the three fundamental visual attributes of spatial detail, color, and motion, spatiochromatic perception deteriorates progressively farther away from the fovea [Gordon and Abramov 1977]. Temporal sensitivity remains unchanged, although certain kinds of animation may still be attenuated imperceptibly. As display sizes increase, therefore, knowledge of peripheral color sensitivity gains importance.

From an applied practical viewpoint, the derivation of visual thresholds under degraded peripheral stimulus conditions is important for the design of large displays, control panels, signboards, signals, and so on. In applications related to computer graphics this amounts to the establishment of limits for peripheral chromatic degradation, i.e., acceptable peripheral chromatic Level of Detail (LOD). In this instance, by acceptable we mean thresholds that do not impede human performance (viz. visual search). To do so, we use color zone maps to create a trichromatic degradation map, or *visual field* (Figure 1), suitable for gaze-contingent display. Color zone maps are quantitative topological indicators of peripheral sensitivity to unique hue components (see below). We evaluate the potential for reduction of peripheral color content by uniformly scaling the color degradation map and slaving its center to the real-time point of gaze measured by an eye tracker. The significance of our contribution is loosely analogous to Ferwerda et al.'s [1996] model of dark adaptation for realistic image synthesis because (gaze-contingent) concentric reduction of peripheral color tends to simulate scotopic viewing conditions.

2. BACKGROUND

2.1 Color Vision in the Fovea and Periphery

The CIE 1931 and 1964 standard colorimetric observer functions are based on perceptual color-matching tasks where the visual test field is viewed by the central region of the retina covering the fovea when the field has an angular subtense not exceeding 2°, and includes the parafoveal region for fields of 10° [Wyszecki and Stiles 1982]. Peripheral regions are therefore largely uninvolved. Contrasted with these conditions, a 17″ flat panel monitor subtends a much larger 47° (diagonal) viewing area (approximately 37° × 30°) at a typical viewing distance of 50 cm. When the test field is moved eccentrically away from the fovea, neither of the standard observer functions applies.

Peripheral color vision deviates significantly from foveal and parafoveal color vision. According to Wyszecki and Stiles, "the 'blue' mechanism in the parafovea (10° field) might become relatively more sensitive compared with the foveal 'blue' mechanism, whereas for the 'green' and 'red' mechanisms, a reverse effect occurs." To quantify peripheral color sensitivity, the CIE charged Technical Committee TC 1-42 (Colour Appearance in Peripheral Vision, est. 1993) with the preparation of a technical report
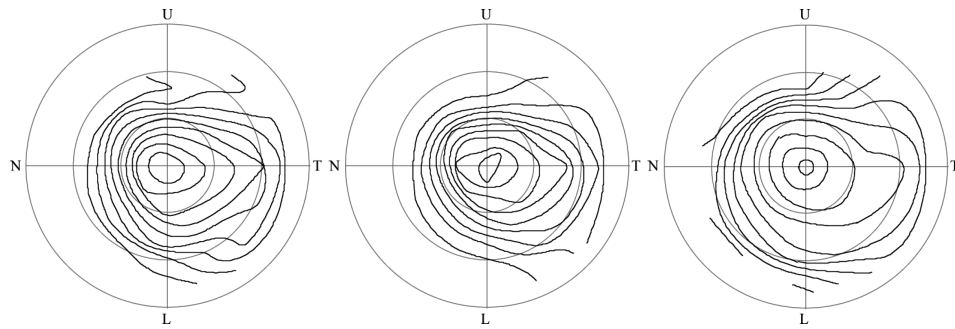
Fig. 2.   Color zone maps of R, G, B, unique hue components (UHCs), respectively. T, U, N, and L indicate the temporal, upper, nasal, and lower directions in the visual field of the right eye. In each panel, the radius indicates the eccentricity in the visual field. The light-gray circles correspond to $30°$, $60°$, and $90°$ eccentricity. Black circles and curves represent the contour lines of the normalized UHC for each stimulus, with values ranging from 0.9 to 0.1 concentrically from the inside. Courtesy of Masato Sakurai.

on color appearance zones for colored lights in terms of unique hues in peripheral vision. The color zone map is a contour map covering the entire $180° \times 180°$ visual field showing how perceived strength of redness, yellowness, greenness, or blueness (referred to as the "Unique Hue Component," or UHC) in a given stimulus changes with eccentricity from the center of the visual field. Figure 2 gives the color zone maps obtained by Sakurai et al. [2003] for UHCs R, G, and B under adaptation to D_{65}-like (photopic) illumination (Hamada and Yujiri [2004] provide similar color zone maps under varying illumination).

Ayama et al. [2004] review the basic aspects of color presentation in the peripheral visual field and report on experiments conducted in Japan and Sweden. Results show that an increase of retinal temporal eccentricity to $40°$ causes impaired color appearance, especially for red and green UHCs. Smaller color stimuli are perceived to be less chromatic than larger color stimuli at increased retinal eccentricities. Generally, blue and yellow UHCs are better perceived than green and red in the periphery. This may be related to the steep decline of L/M cone opponency (red-green) across the retina, which becomes behaviorally absent by $25°$ to $30°$ (in the nasal field) [Mullen et al. 2005], even though the presence of a high proportion of ganglion cells sensitive to red-green modulation far out in the periphery ($20°$ to $50°$ of macaque retina) has been reported [Martin et al. 2001]. Any L/M cone-opponent neurons found in the primate retina beyond $30°$ eccentricity are unlikely to be significant for color contrast detection measured behaviorally. The reason for this is likely due to weaker spatiotemporal coherence of neuronal signals in the parvocellular afferent pathway in peripheral than in foveal retina [Solomon et al. 2005]. Peripheral detection of blue and yellow may be a consequence of S/(L+M) cone opponency (blue-yellow), which is relatively more evenly distributed across the visual field. There is evidence that the retinal circuitry for blue-on chromatic selectivity is preserved at least to $40°$ eccentricity [Solomon et al. 2005]. However, Mullen et al. [2005] note that the two cone-opponent mechanisms, when activated individually by cardinal stimuli, do not give rise to the color sensations of unique red, green, blue, or yellow and so should not be confused with the color-opponent processes. Martin et al. [2001] suggest that psychophysically demonstrated deterioration of peripheral color discrimination is likely further influenced by postretinal mechanisms.

2.2   Testing Peripheral Perception Via Tachistoscopic and Gaze-Contingent Paradigms

Evaluation of peripheral color vision, as was done in preparation of the color zone maps of Figure 2, relies on peripheral color-matching experiments, a type of discrimination test wherein a *fixation target* is

viewed foveally, with a *test field* subsequently imaged at a specific peripheral location. A hemispherical display is used to image peripheral test fields, with the viewer's gaze point at any given instant assumed to be fixed at the apex of the hemisphere. Unless the viewer's eye gaze is monitored or recorded in some way, the viewer's fixation can only be assumed to coincide with the central target just prior to brief exposure (e.g., 1 s) of the peripheral test field. Much briefer exposures (e.g., 0.25 s) are common in so-called tachistoscopic studies. The rationale behind limited duration of stimulus exposure is that the period will be too brief to allow a saccadic eye movement away from the central fixation target. However, saccadic eye movements can be quite fast. Depending on their amplitude (angular distance required for the eye to rotate), saccade durations can be as short as 10 ms [Shebilske and Fisher 1983]. In fact, saccadic eye movements are of sufficiently short duration to render the executor effectively blind during the transition. This phenomenon is known as *saccadic suppression* and is known to precede a saccade (i.e., neurological functions are implicated in suppression of the retinal signal). Without explicit measurement or monitoring of the initial gaze position, it is difficult to verify the viewer's continued fixation of the central target during peripheral field presentation.

As an alternative to the tachistoscopic paradigm in discrimination tasks, an eye tracking device can be used to record the user's eye gaze during stimulus exposure. In visual search tasks, a moving window (or mask) can be translated over the stimulus, synchronized to the user's real-time gaze point. When manipulating the peripheral visual field, the translation of the synchronized foveal region should ideally match saccadic velocity. Unless the terminating coordinates of the saccade can be predicted with any accuracy, this is generally impossible due to eye tracker lag. Eye trackers operating at 1,000 to 2,000 Hz are commercially available but they are expensive and difficult to operate, often requiring bite bars to maintain head stability. The eye tracker used in the present study operates at 50 Hz, inducing at least a 20 ms lag in gaze-contingent update. This rather long delay is problematic for generation of gaze-contingent displays that are intended to be indistinguishable from full-resolution displays where spatial resolution is reduced peripherally. For example, a previous study suggested that gaze-contingent displays must be updated within 5 ms to avoid detection [McConkie and Loschky 2002]. However, because that study did not vary image resolution as a function of retinal eccentricity, its deadline is overly conservative for our purposes. A more recent study using gaze-contingent multiresolutional displays has shown that delays as long as 60 ms do not increase the detectability of peripheral image degradation [Loschky and Wolverton 2007]. We assume the same holds for chromatic degradation during visual search, which should be even less sensitive to delays than detection [Loschky and McConkie 2000].

This article seeks to complement previous work on gaze-contingent spatial and temporal degradation by evaluating peripheral chromatic sensitivity. In doing so, our empirical analysis is based on metrics of performance, not perception. Perceptual thresholds are in a sense more stringent than those of performance because it is possible to maintain performance (e.g., speed or accuracy) in an environment that is perceptibly degraded, but generally not vice versa (i.e., one can notice the degradation but still function within normal limits whereas evaluation of a just noticeable difference is another matter). Following the work of Watson et al. [1997, 2004], we use coarse-grained LOD manipulation (three levels of degradation) but slave our moving window to the direction of eye gaze, not the head. Our gaze-contingent paradigm is similar to that of Murphy and Duchowski [2002], who simulated Watson et al.'s conditions with an eye tracker, as well as to that of O'Sullivan et al. [2003] and Böhme et al. [2006] who used an eye tracker to perform tests of peripheral temporal (motion) degradation.

Past work rooted in the gaze-contingent experimental paradigm is reviewed in more detail in the subsequent section. Details of creation of color degradation maps follow and precede a description of our experimental methodology. Results are then given with recommendations for extents of peripheral chromatic degradation.

3. RELATED WORK

Gaze-contingent displays, or GCDs, have been used for the purpose of studying visual perception for over 30 years. By removing information beyond perceptual limits, GCDs match the resolvability of human vision. GCDs extend the classic one-dimensional "moving window" experimental paradigm [McConkie and Rayner 1975], originally developed for reading studies, to two and three dimensions through real-time spatiotemporal degradation of model geometry or pixel resolution [Duchowski et al. 2004; Parkhurst and Niebur 2002; Reingold et al. 2003]. GCDs can increase display bandwidth through compression of peripheral image information not resolvable by the viewer. Potential applications include flight and driving simulators, virtual reality, infrared and indirect vision, remote piloting, robotics and automation, teleoperation, and telemedicine; image transmission and retrieval, and video teleconferencing [Baudisch et al. 2003; Reingold et al. 2003]. GCDs have also inspired a nongaze-contingent approach to video telephony where face detection invoked a visual eccentricity model of the human visual system's contrast sensitivity function, or CSF, to peripheral compression [Daly et al. 2001]. Here we briefly summarize pertinent graphics-related results to establish context for the present study. Specifically, we list previous work related to peripheral reduction of head- or gaze-contingent spatiotemporal detail at both screen and geometry levels. However, to our knowledge, peripheral color reduction has not yet been investigated in a gaze-contingent manner.

Model-based LOD manipulation involves detail reduction of geometric models at distance as well as eccentricity. Notable gaze-contingent examples include the work of Levoy and Whitaker [1990], Ohshima et al. [1996], Luebke and Erikson [1997], Murphy and Duchowski [2001], and Parkhurst and Niebur [2004]. In most cases, some improvement in rendering speed is reported due to peripheral polygon count reduction. Watson et al. [2004], who provide additional model-based examples, point out that speed improvement may be limited if only a subthreshold approach is used to reduce detail. Spatiochromatic peripheral degradation investigated in this paper is performed at the pixel level. Although color reduction may be applicable to geometry rendering, geometric LOD reduction falls outside the scope of this article. Here, we mainly consider prior results from pixel-based LOD manipulation.

A GCD is said to be perceptually lossless for a specified viewing distance and (instantaneous) gaze direction if the reconstructed display and the original appear identical to human observers when viewed from the specified distance (cf. perceptually lossless image compression [Hahn and Mathews 1997]). It is important to distinguish perceptual effects from ones of performance when reducing peripheral detail (e.g., cycles per degree or bits per pixel) or peripheral color.

Loschky and McConkie [2002] conducted an experiment on a two-region gaze-contingent display, in which they factorially combined three sizes of central high-resolution region (or "window"), ranging from $1.6°$ to $4.1°$ radius, and three levels of peripheral resolution, in order to investigate the spatial and resolutional parameters affecting perception and performance. They found that with a window radius of $4°$, search times and fixation durations were essentially normal (no different from an all high-resolution control condition), though saccade lengths were somewhat more sensitive to loss of peripheral image resolution even in the $4°$ radius window. Their results suggest that the generation of a perceptually lossless GCD is quite difficult in comparison to the generation of a GCD that does not deteriorate performance (but see Loschky et al. [2005], which bracketed a perceptually lossless GCD, between highly perceptible and completely imperceptible peripheral image degradation conditions).

Parkhurst et al. [2000] investigated behavioral effects of a two-region gaze-contingent display. A central high-resolution region, varying from $1°$ to $15°$, was presented at the instantaneous center of gaze during a visual search task. Measures of reaction time, accuracy, and fixation durations were obtained. Reaction time and accuracy were found to co-vary as a function of the central region size.

For small central region sizes, slow reaction times were accompanied by high accuracy. Conversely, for large central regions sizes, fast reaction times were accompanied by low accuracy. In agreement with reaction time and accuracy, fixation duration was approximately normal (comparable to that seen for uniform resolution displays) with a window radius of $5°$. However, window size and level of central and peripheral resolution were confounded in this study, making interpretation of this result difficult. Nevertheless, the results are comparable to those found by Loschky and McConkie [2002] with a $4°$ window.

Contrasted with its effect on visual perception, we limit our investigation of peripheral color degradation to its effect on performance during visual search, in a manner similar to Watson et al.'s [2004] investigation of suprathreshold control in a head-centric head-mounted display ($75.3° \times 58.4°$ field of view). In earlier work Watson et al. [1997] used a similar experimental setup to evaluate spatial and chrominance detail degradation. They suggested that visual spatial and chrominance complexity can be reduced up to $30°$ visual angle by almost half without impeding search performance. Although their findings are relevant, they did not use an eye tracker to verify gaze coordinates or control the display. We use a smaller, desktop display and slave our foveal region to (x, y) gaze coordinates with an eye tracker.

Gaze-contingent displays have also been used to study the reduction of temporal detail, that is, motion. In a model-based approach, O'Sullivan et al. [2003] used a GCD to evaluate the peripheral reduction of collision distance between complex geometric objects. Their purpose was to identify a suitable metric of visual fidelity of animation. Böhme et al.'s [2006] GCD degrades temporal content as well as spatial content, extending Geisler and Perry's [2002] pyramidal preprocessing approach into the temporal dimension. Peripheral motion reduction produces rather interesting effects (e.g., high-frequency movement can all but be eliminated). Böhme et al. report that such manipulation reduces the number of high-amplitude saccades and can remain unnoticed by the observer. We do not consider peripheral motion in our study.

Geisler and Perry's [2002] work on the simulation of arbitrary visual fields is relevant here because they were the first to separate the peripheral degradation function from the stimulus image (i.e., the stimulus image need not be degraded a priori). Furthermore, the peripheral degradation function is itself specified as a smoothly ramped image (e.g., alpha channel where 1 indicates preservation of spatial detail and 0 decimation). In contrast, Watson et al.'s dual viewports are limited to the display of two distinct regions. It is unlikely that the latter approach lends itself to the simulation of arbitrary visual fields. Indeed, Reddy [2001] noted that practically all perceptually based work (up to that point) had used a small set of presimplified versions of an object from which to choose to render in a view-dependent manner (this is often the chosen model-based approach, dating back to Clarke's [1976] originally proposed method of simplifying the resolution of geometric objects as they recede from the viewer that is now accepted as standard practice, particularly in real-time environments [Funkhouser and Séquin 1993; Vince 1995]). It seems that an a priori preprocessing style of gaze-contingent rendering is still the predominant approach for image-based synthesis. For example, Reddy's *Percept* visualization performs a per-pixel calculation of the pixel's spatial frequency based on angular velocity and eccentricity, while Çöltekin's [2006] *Foveaglyph* builds a pyramid of scaled images, in a manner similar to that of Geisler and Perry and Böhme et al.

Instead of a priori assembly of a pre-processed image hierarchy, we use a GPU-based GCD where the stimulus image pyramid is created and stored as a mipmap texture. A GL shading language (GLSL) fragment program is invoked to recall subsampled versions of the mipmapped image to produce the peripherally degraded effect. Due to hardware-assisted subsampling of a given image, the GPU-based GCD obviates the need for image preprocessing. Duchowski and Çöltekin [2007] provide a chronological review of GCD-based approaches as well as its evolution to its present GPU-based implementation.
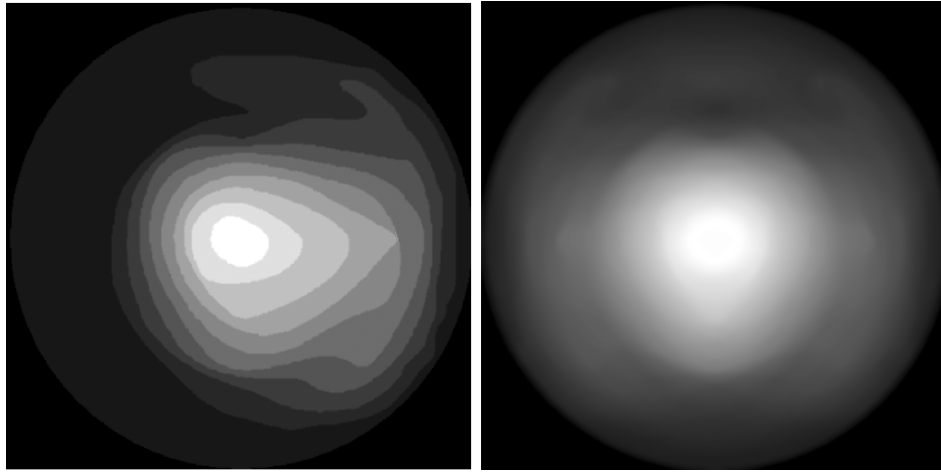
Fig. 3. Creation of color degradation maps. The discretized R channel color zone map for the right eye is shown at left. At right is the mirrored Gaussian-blurred color degradation map used in the experiment.

4. METHODOLOGY

The objective of the experiment was to quantify the effect of peripheral color sensitivity on visual search performance. We hypothesized that the reduction of peripheral chromatic information would degrade performance in terms of both speed and accuracy.

4.1 Color Degradation Mapping

Color degradation maps were created manually in PhotoShop by assigning each pixel's greyscale value to its corresponding contour value found in Sakurai et al.'s [2003] UHC color zone maps shown in Figure 2. This resulted in discretized degradation maps similar to the R channel map shown at left in Figure 3. Because each color zone map specifies the visual color sensitivity of only one eye (the right eye), each map was mirrored about the y-axis to produce a map suitable for binocular viewing, under the assumption of symmetry.

To reduce Mach banding, a Gaussian mask was used to smooth each of the channel maps. Finally, all three maps were assembled into a trichromatic $1,024 \times 1,024$ master map shown in Figure 1 (fourth from the left). The master map's original square aspect ratio was preshrunk to meet the outstretched texture coordinate projection to a $1,280 \times 1,024$ viewport (see Section 4.5 Experimental Design below).

4.2 Gaze-Contingent Display

Peripheral degradation of spatial and color detail is accomplished with the use of a 4-channel texture map. The R, G, B channels of the map reduce color information via linear interpolation between chrominance and luminance, where the interpolant is the degradation map value $I(x, y) \in [0, 1]$ at pixel coordinates (x, y). A simple but common color to luminance tone mapping formulation is used; for details see the GLSL fragment program for computing eccentric spatiochromatic degradation at (x, y) gaze coordinates in Listing 1.

Spatial degradation is normally obtained by a similar mechanism where the degradation map's alpha channel serves as the interpolant for selection of mipmap level at the (x, y) pixel. For example, a value of 1 selects the pixel from the bottom (finest detail) level of the mipmap pyramid. In the present experiment

```
uniform float min_lod;
uniform sampler2D img_tex, deg_tex;

void main(void)
{
  // rgb→lum coefficient vector (from Foley et al. [1990])
  vec4 lum = vec4(0.299, 0.587, 0.114, 1.0);

  // fetch degradation texture sample
  vec4 deg = texture2D(deg_tex, gl_TexCoord[1].st);

  // invert lod mapping
  float lod = (1.0 − deg.w) * min_lod;

  // fetch lod biased image texture sample
  vec4 rgb = texture2D(img_tex, gl_TexCoord[0].st, lod);

  // return final composite
  gl_FragColor = vec4(rgb.xyz * deg.xyz, rgb.w) +
      dot(lum.xyz, (rgb.xyz * (1.0 − deg.xyz)));
}
```

Listing 1. GLSL fragment program for computing eccentric spatiochromatic degradation at gaze point from an arbitrary 4-channel degradation texture map. The three chroma channels degrade the corresponding R, G, B color components while the alpha channel degrades spatial detail by selecting the appropriate mipmap level. Reproduced for convenience from Duchowski and Çöltekin [2007] © ACM. A simple mouse-based GLUT example is also available on the Web: <http://andrewd.ces.clemson.edu/gcd/>

a fully opaque alpha channel (all ones) is used producing no spatial degradation in the periphery. See Duchowski and Çöltekin [2007] for further technical details.

4.3 Apparatus

A Tobii ET-1750 video-based corneal reflection (binocular) eye tracker was used for real-time gaze coordinate measurement (and recording). The eye tracker operates at a sampling rate of 50 Hz with an accuracy typically better than $0.3°$ over a $±20°$ horizontal and vertical range using the pupil/corneal reflection difference [Tobii Technology AB 2003] (in practice, measurement error ranges roughly $±10$ pixels). The display program's average refresh rate was informally measured at 34 fps (above the monitor's physical refresh rate of 30 Hz). The eye tracker's 17″ LCD monitor was set to 1,280 × 1,024 resolution and the stimulus display was maximized to cover the entire screen (save for its title bar at the top of the screen). The eye tracking server ran on a dual 2.0 GHz AMD Opteron 246 PC (2 G RAM) running Windows XP. The client display application ran on a 2.2 GHz AMD Opteron 148 Sun Ultra 20 running the CentOS operating system. The client/server PCs were connected via the departmental 1 Gb Ethernet (both connected to a switch on the same subnet). Although the Tobii allows limited head movement (30 × 15 × 20 cm volume), a chin-rest was used to restrict such movement and maintain constant distance (50 cm) from the monitor.

A 9-point calibration sequence is used to calibrate the eye tracker to the individual. The eye tracker samples the eye camera image at each of the 9 calibration points, and uses these as markers to interpolate (x, y) coordinates of the user's gaze over the remaining screen surface.
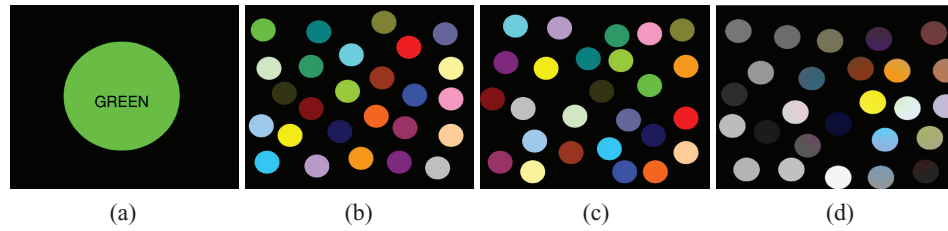
Fig. 4. *Green* target screen (a) and two examples of corresponding control search field screens (b–c) with no peripheral chromatic degradation. The fourth image (d) shows an example screenshot showing 20° peripheral color degradation with current point of gaze at the upper-right edge of the yellow target (approximately fourth from the left and third from the bottom). Peripheral degradation follows the point of gaze which is free to move naturally. As it is being tracked at 50 Hz, the display is updated in a gaze-contingent manner every 20 ms.
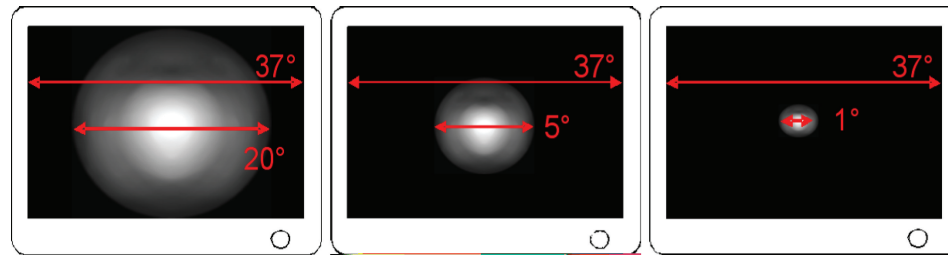

Fig. 5. Illustration of the color maps' sizes relative to the monitor used in this study. From left to right, the images show the map scaled down to subtend 20° (horiz.), 5°, and 1°, respectively.

4.4 Stimulus

Stimuli used in this study consisted of 12 different static display screens. Each screen contained 25 uniquely colored discs of the same size and shape, differing only in their spatial arrangement. Prior to each search task, the participant was provided a visual reference of the target color (see Figure 4). Three target colors were used: red, green, and blue, coded simply in RGB space as $(255, 0, 0)$, $(0, 255, 0)$, and $(0, 0, 255)$, respectively.

4.5 Experimental Design

The independent variable in this study was visual field size, or visual window size, which spanned 10% of the monitor (128×102 pixels, visual angle 1°), 50% of the monitor (640×512 pixels, visual angle 5°), 90% of the monitor ($1,152 \times 921$ pixels, visual angle 20°), and no moving window at all (control). The angular field subtense is calculated assuming 50 cm viewing distance. The color maps' sizes relative to the monitor are illustrated in Figure 5.

Dependent variables consisted of time to complete a color identification search task and accuracy of locating the correct target upon identification. Time to complete the task was recorded from the start of the search task to the time the color was identified. Participants were instructed to advance to the next (static) image by pressing the Enter key as soon as they located the target.

Accuracy was measured by comparing the target's screen coordinates with the viewer's gaze within 500 ms of the viewer's pressing the Enter key to signal (perceived) target detection. If gaze coordinates for both eyes in this interval were found within 2 diameters of the target disc, a 1 was recorded, otherwise a 0 was registered.

The experiment was based on a within-subjects design wherein each participant performed 4 search tasks for each of the three UHC targets for each visual field size ($1°$, $5°$, $20°$, and control), resulting in a total of 48 trials. Trial order was counterbalanced by a Latin square.

4.6 Participants

A total of nine individuals participated in this study. The participants were university students and faculty between the ages of 21 and 40. There were five males and four females all with self-reported 20/20 corrected vision (acuity). Participants were screened for correct color vision with an Ishihara pseudoisochromatic plate test.

4.7 Procedure

Reading from a script, each participant was greeted by the experimenter and briefed on the nature of the study. Next, each participant answered a demographic questionnaire and was screened for normal color vision. Following calibration an SMPTE color bar stimulus was presented to familiarize the viewer with the gaze-contingent display. At this stage, the eye tracking calibration was qualitatively evaluated. If the viewer reported sufficient deviation of the gaze-contingent color field from proprioceptive gaze coordinates, the eye tracker was recalibrated.

Each participant was required to locate each of the three UHC targets during each block of trials. For each UHC target search, the participant would first view the target screen, which served as an indication of which UHC to be searching for (e.g., green). After pressing the Enter key, they would then search for the green disc in the field of distractors, once again pressing the Enter key as soon as they had located it. Participants were told that their response was being timed, but the search was otherwise self-paced. Participants would repeat the search for a UHC target four times before moving on to the next UHC target. The order of UHC targets was counter-balanced so as not to introduce learning or fatigue bias during search for any one particular hue. Upon completion of all 48 search tasks, the participant was thanked and dismissed.

5. RESULTS

One-way ANOVA suggests the effect of window size on time to completion is significant ($F(3,428) = 22.6943$, $p < 0.01$). Pairwise comparisons using t-tests with pooled SD and Bonferroni adjustment reveal a significant difference ($p < 0.01$) in time to completion between all pairs of conditions except the window of $20°$ and control and the windows of $20°$ and $5°$. The difference in time to completion with the window of $5°$ and control is significant at $p < 0.05$. Mean completion times are shown graphically in Figure 6.

Average accuracy was computed by counting the number of 1 entries obtained under each gaze-contingent condition. An observer could score a maximum of 4, for each of the R, G, B UHC targets because each observer performed four viewing trials per UHC block. In all, 12 such entries were recorded for each participant. Values for the R, G, B UHCs under each gaze-contingent condition were then pooled for comparison. One-way ANOVA suggests the effect of window size on accuracy is significant ($F(3,104) = 7.2084$, $p < 0.01$). Pairwise comparisons using t-tests with pooled SD and Bonferroni adjustment reveal a significant difference ($p < 0.01$) in accuracy between the window of $1°$ and each of the window of $20°$ and the control condition. No other significant differences were found. Represented as average percentage targets fixated correctly, accuracy is shown graphically in Figure 7.

6. DISCUSSION

Because our degradation maps were modeled on Sakurai et al.'s [2003] color zone maps, it is not surprising that our results, suggesting a relatively shallow eccentricity-dependent drop-off of chromatic
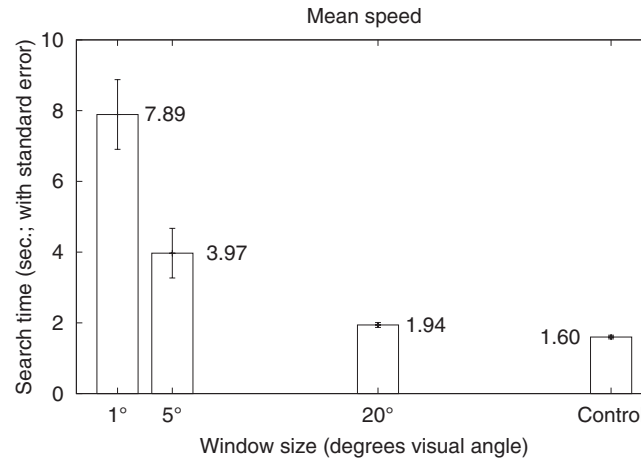
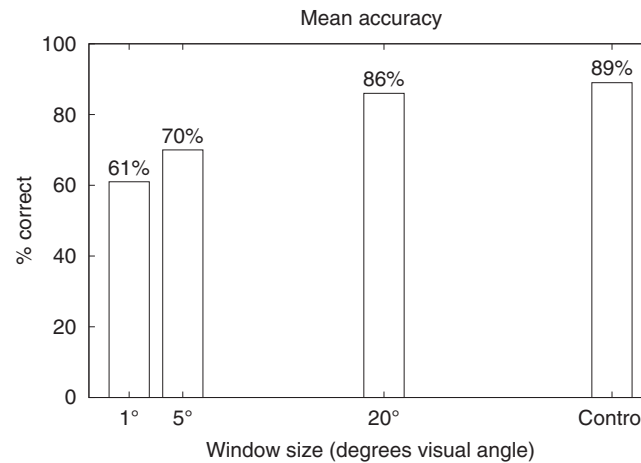Fig. 6. Mean search times (in seconds) versus window size.

Fig. 7. Mean search accuracy (% correct) versus window size.

sensitivity, are consistent with theirs (which showed that there was little loss of chromatic information within the central $20°$ visual angle). Recall that Sakurai et al.'s [2003] original color zone maps were developed under adaptation to D_{65}-like (photopic) illumination. According to Hamada and Yujiri [2004], peripheral color zone maps shrink concentrically under illumination conditions approaching scotopic vision. By artificially scaling our color degradation maps from Sakurai et al.'s [2003] original maximum of $90°$ eccentricity to our maximum of $20°$, we are effectively simulating reduced peripheral color sensitivity (namely under scotopic lighting conditions).

Results suggest that artificial reduction of chrominance in the periphery significantly degrades search performance when the gaze-contingent window is $5°$ or smaller. This implies that, for visual search at least, vision is more sensitive to peripheral color than spatial detail because performance during gaze-contingent search with a $5°$ window is comparable to that seen for uniform resolution displays (see Parkhurst et al. [2000] and Loschky and McConkie [2002]; note that Loschky and McConkie's

$4°$ window that produced roughly equivalent performance and eye movement measures to the control condition may be a better estimate of a critical window size although estimates from both studies are somewhat similar). For viewers to achieve performance comparable to that of a uniform color display, a window of $20°$ is required.

Our speed results also appear consistent with Watson et al.'s [1997] earlier work on head-contingent degradation, who suggested that visual spatial and chrominance complexity can be reduced up to $30°$ visual angle. Our study suggests that chrominance alone can be further reduced down to $20°$ without affecting search performance (we did not alter spatial resolution in this experiment). Ecologically, this agrees roughly with the dimension of the macula, which extends to about $16.7°$ at which juncture the population of retinal cone photoreceptors drops to well below 20,000 per mm^2 [Haber and Hershenson 1973].

Our accuracy results indicate that with a small foveal window, slow reaction times are accompanied by poor accuracy. Conversely, with a large foveal window size, fast reaction times are accompanied by high accuracy. These results seemingly contradict Parkhurst et al.'s [2000] findings, where reaction time and accuracy were found to co-vary as a function of the size of foveal window. There, accuracy was operationalized by recording a correct response if, at the time of the response, eye gaze fell within $1°$ of the target. Furthermore, it was repeatedly stressed to participants that accuracy was the most important quality of the response expected of them. The result was a clear indication of a strategic speed/accuracy tradeoff where participants favored speed in some conditions and accuracy in others. It is well known that eye movement patterns (scanpaths) are task-dependent. Given explicit instruction to maintain accuracy, participants may have shifted their bias from favoring speed at large foveal window sizes to favoring accuracy at smaller window sizes.

In our case, as in Parkhurst et al.'s [2000] study, gaze position was used to indicate the location of the selected target. We considered the response correct if gaze fell within two circle diameters ($8°$) of the target. However, no explicit instructions were given to participants to fixate the target upon its detection (i.e., accuracy was not stressed as the most important quality of the response). Rather, by informing participants that their response was timed, implied emphasis was placed on speed. It is, therefore, likely that participants did not shift their strategic bias from speed to accuracy. Instead of an indication of a strategic speed/accuracy tradeoff, our measure of accuracy is more likely a reflection of the cumulative probability of target perception and is suggestive of a direct link to visual search coverage.

Why should the level of accuracy under normal viewing conditions (control) only reach 89%? The 11% average "error" is likely an indication of (implied) task emphasis on speed rather than accuracy, eye tracker measurement error, or a combination of both factors. Assuming consistent eye tracker error, accuracy results may be an indicator of viewers' tendency to disperse gaze as a function of restricted peripheral color sensitivity. Encumbered by smaller foveal window sizes, viewers may be more active in integrating chrominance information across the visual field. If so, this is an illustration of classic scene integration where the human visual system strives to coalesce into a coherent whole a visual field that is obtained piecemeal by foveal vision.

7. MODELING SEARCH PERFORMANCE

Search performance can be modeled by fitting an exponentially decaying function to the observed mean completion times with variable window size, that is, $y = ax^b$ with $a = 7.91$ and $b = -0.44$ (reduced $\chi^2 = 0.016$), as shown in Figure 8. Such curve fitting may provide a useful asymptotic rule of thumb for search performance with decreased peripheral color sensitivity, however, it does not provide an explanation of the observed behavior. A more practical approach should strive to derive an ideal observer theory of visual search, for example, for targets in broadband noise [Najemnik and Geisler
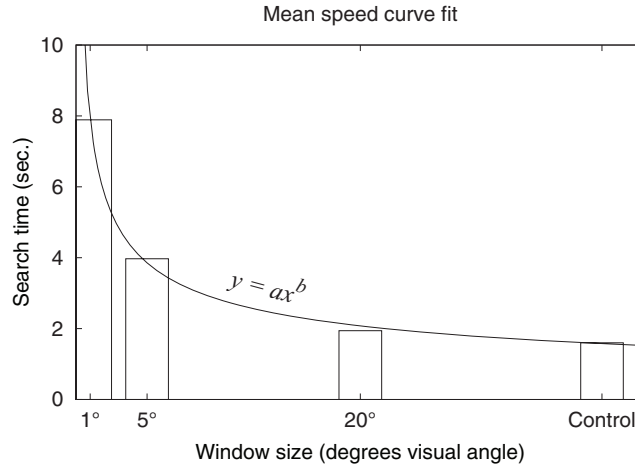
Fig. 8. Fitting observed performance (mean time to completion) data with $y = ax^b$, $a = 7.91$ and $b = -0.44$.

2005]. The ideal searcher would provide the appropriate benchmark against which to compare observed performance and a useful starting point for proposing realistic (suboptimal) models of visual search [Geisler et al. 2006].

Melloy et al.'s [2006] model of extended, semisystematic visual search may serve as a more suitable predictor of search performance if it can be adapted to the present conditions. To do so, the process of searching a field for targets is defined as a series of fixations, where the search field is assumed to be homogeneous (there are no distinctive regions, visually or otherwise). The search field is represented as a set of equal-sized cells, with cell size corresponding to the area that can be encompassed in a single fixation. Each successive fixation either deliberately glimpses a cell not yet fixated in a systematic manner or arbitrarily glimpses a cell at random. For a target to be located, a cell must first be fixated before the target is subsequently perceived. It is assumed the targets are inconspicuous, precluding the possibility of guided search Wolfe [1994]. Visual search is then modeled as a discrete-time nonstationary Markov process $x_t = (k, \mathbf{l}, m)$, where k is a nonnegative integer corresponding to the number of distinct cells that have been fixated, $\mathbf{l}$ is a vector of h elements where each l_j element denotes the number of type j targets in the search field, and m is a binary variable indicating whether or not a fixated target has been perceived, that is,

$$m = \begin{cases} 0 & \text{when target is not perceived on } t\text{th fixation, or} \\ 1 & \text{when target is (fixated and) perceived on } t\text{th fixation.} \end{cases}$$

The model is intended to represent a semisystematic search that terminates upon detection of a target. Several parameters characterize the search:

—a: area of search field, $a \in \mathbf{R}$, $a > 0$,
—o: visual lobe, that is, area of individual cell, $o \in \mathbf{R}$, $o > 0$,
—b_j: number of type j targets, $j = 1, 2, \ldots, h$, $b_j \in \mathbf{Z}^+$,
—h: number of different target types in search field, $h \in \mathbf{Z}^+$,
—g: search time upper limit (in seconds), $g \in \mathbf{R}$, $g > 0$,
—$f = \lfloor g/0.3 \rfloor$, fixation number upper limit, in which 0.3 s is the assumed duration of a single fixation,
—ρ_j: perceptual sensitivity, that is, the proportion of time that a type j target is perceived, given that the cell that contains it has been fixated, $\rho_j \in [0, 1]$, $j = 1, 2, \ldots, h$.
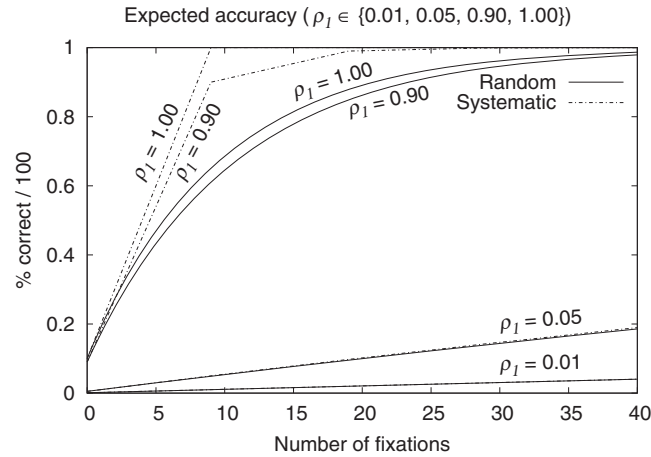
Fig. 9. Modeled expected accuracy versus number of fixations at perceptual sensitivity levels $\rho_1 \in \{0.01, 0.05, 0.90, 1.00\}$ with abscissa curtailed for clarity.

At its core, the model relies on the notion of *systematic search efficiency*, defined as the probability of a random or systematic fixation at time t, $\varepsilon_t \in [0, 1]$, $t \in \mathbf{Z}^*$. The nature of a fixation depends on the corresponding search strategy assumed by the viewer. Systematic and random fixations are analogous to sampling without and with replacement, respectively. Consequently, $\varepsilon_t = 0$ indicates a fully random (memoryless) and least efficient search, while $\varepsilon_t = 1$ indicates a fully systematic and optimally efficient search. Human visual search is expected to fall somewhere between these two extremes.

Depending on the modeled strategy (random or systematic), expected time to completion and accuracy are computed as functions of the number of fixations cast over the search field. Accuracy is defined as the cumulative probability of target perception by the tth fixation and is related to the notion of *field coverage*—the number of distinct cells fixated by time t in the initial scan of a field void of targets, relative to the number of cells in the field. Coverage, in turn, is directly related to the degree of systematic efficiency. In the case of strictly systematic search, field coverage is equal to 1 (unity, or 100%) when the number of fixations corresponds to the field size. Expected field coverage of searches imbued with a random component will approach but never reach unity because complete coverage cannot be guaranteed when any random behavior is exhibited.

Generally, the model will reach a search time upper bound provided enough fixations have been cast for the target to have been perceived. Expected time to completion is modeled as the average time to target perception for a given (simulated) time span, t. As such, average time to perception will always be less than or equal to t. Relatively less systematic searches exhibit completion times that are initially shorter and later longer than more systematic searches. The reason for this is that when the less systematic searches are successful, it is more likely that they will be successful early on. This initial advantage is negated as the time horizon is extended, however, because protracted searches are more likely to be the by-product of less efficient behavior. Moreover, because it is less likely that these searches will be successful, the expected completion time curves reflect the fact that less efficient searches are consistently more time consuming on average.

In the present case, $a = 37°$, $o = 140$ pixels, or $4°$ visual angle, $n = \lceil a/o \rceil = 10$, $j = 1$, $b_1 = 1$, $g = 90$ (seconds), $f = \lfloor g/0.3 \rfloor = 300$, $h = 1$. Perceptual sensitivity, $\rho_1 \in \{0.01, 0.05, 0.90, 1.00\}$, represents the independent variable of the experiment, namely color sensitivity that is artificially controlled via the extent of the gaze-contingent window.
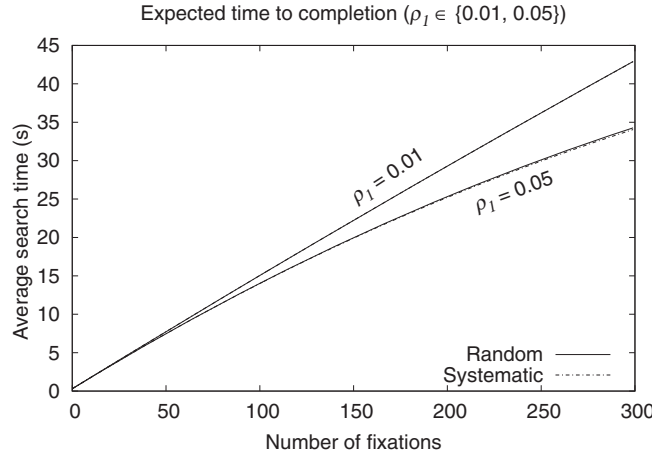
Fig. 10. Modeled expected time to completion vs. number of fixations at perceptual sensitivity levels $\rho_1 \in \{0.01, 0.05\}$.
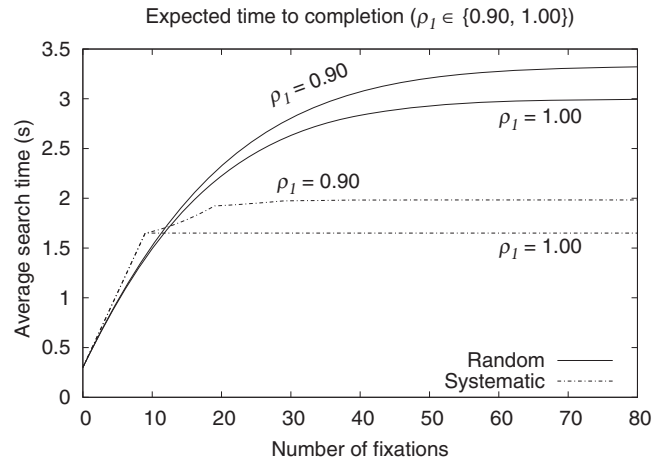

Fig. 11. Modeled expected time to completion versus number of fixations at perceptual sensitivity levels $\rho_1 \in \{0.90, 1.00\}$ with axes curtailed for clarity.

Modeled accuracy, as seen in Figure 9, is predicted at 87% in about 2.7 to 6 s (9 to 20 fixations) with $\rho_1 \in \{0.90, 1.00\}$. Human observers reached this level of accuracy in less than 2 s at this high level of peripheral sensitivity. With $\rho_1 \in \{0.01, 0.05\}$, human observers reached 61% and 70% accuracy within 4 and 8 seconds, respectively. At these lower levels of sensitivity, the model does not clearly distinguish between systematic and random search strategies and predicts 70% accuracy within 72 s with $\rho_1 = 0.05$ but with $\rho_1 = 0.01$ fails to reach 61% accuracy within 90 s (simulation duration). In essence, the model underestimates human search efficiency.

As shown in Figure 10, with $\rho_1 \in \{0.01, 0.05\}$, the model fails to bound the estimated time to completion at 300 fixations and predicts expected search time in excess of 20 s. The observed average search time for both cases is less than 10 s. As with modeled accuracy, the interesting aspect of the model's prediction at these low levels of perceptual sensitivity is the lack of distinction between random and systematic strategy.

Remarkably, the model fairly closely predicts observed average completion times at $\rho_1 \in \{0.90, 1.00\}$ (Figure 11). Expected search time approaches about 3 s with a random search strategy and just under 2 s with a systematic strategy (1.98 s and 1.65 s at $\rho_1 = 0.90$ and $\rho_1 = 1.00$, respectively). Human searchers outperform the model on average with completion times slightly faster than those of predicted systematic performance (1.94 s and 1.60 s at $\rho_1 = 0.90$ and $\rho_1 = 1.00$, respectively).

Given the specified parameters, the semisystematic visual search is overly conservative in its prediction of absolute performance, its depiction of relative performance serves as a plausible explanation of human behavior. During extended searches, viewers may start visual search with a random strategy (first few fixations) before adopting a semisystematic tactic. Reduced peripheral chromatic sensitivity (as modeled by ρ_j) may delay transition to the semisystematic strategy and result in less efficient search, one that is indistinguishable from an inefficient, random progression.

8. CONCLUSION

Color zone maps were used to construct corresponding color degradation maps (visual fields) for evaluation of spatiochromatic peripheral sensitivity. With the tacit caveat that the trichromatic color degradation map is under gaze-contingent control, the map constitutes a self-contained model of peripheral color sensitivity under variable light conditions. Simulation of peripheral color sensitivity under adaptation to D_{65}-like (photopic) illumination is accomplished by scaling the degradation map so that it extends to $20°$ or beyond (ideally covering the entire $180° \times 180°$ field of view however impractical that may be in an applied setting). Simulation of scotopic illumination, akin to Ferwerda et al.'s [1996] model of dark adaptation, is achieved by scaling the degradation map to considerably smaller extents (cf. Hamada and Yujiri [2004]).

With the degradation map center slaved to the point of gaze with an eye tracker, results from a visual search task suggest that chromatic sensitivity extends to $20°$ visual angle, roughly coinciding with the $16.7°$ extent of the macula. Although similar to the exponential sensitivity falloff of peripheral spatial detail (visual acuity), peripheral color sensitivity does not wane as quickly. For peripheral LOD management, this implies that color detail cannot be reduced as readily as geometric or pixel detail. Abrupt reduction of peripheral color may especially impede prolonged performance where visual search is involved, for example, over large displays, virtual control panels, signboards, signals, and the like.

It is interesting to note that observed relative mean search times (Figure 6) resemble those reported by Parkhurst and Niebur [2004] for peripheral geometric LOD reduction. Provided a model can be suitably reparameterized to predict such results, it may then be generalizable to the description of other forms of peripherally degraded gaze-contingent search performance beyond the effects of chrominance.

We must note that this study is limited to measurement and modeling of performance, that is, time to complete visual search and, to a somewhat lesser extent, search accuracy (recall that accuracy was not emphasized in instructions to participants). We do not report, nor do we model process measures, that is, indications of how the search was conducted, as is often done via analysis of eye movements. In this article, we concentrate on the interactive use of the eye tracker and do not report any relation of search performance to eye movement metrics (e.g., number of fixations, fixation durations, number of saccades, or saccade lengths). Further research should at least consider the effect of chromatic window size on fixation duration and saccade length—two measures that generally show strong effects of peripheral degradation in gaze-contingent viewing.

thanks to Nathan Cournia for developing the original GCD `Cg` code on which the final `GLSL` version is based.

REFERENCES

AYAMA, M., SAKURAI, M., CARLANDER, O., DEREFELDT, G., AND ERIKSSON, L. 2004. Color appearance in peripheral vision. In *Human Vision and Electronic Imaging*. SPIE, Bellingham, WA.

BAUDISCH, P., DECARLO, D., DUCHOWSKI, A. T., AND GEISLER, W. S. 2003. Focusing on the essential: Considering attention in display design. *Comm. ACM 46*, 3, 60–66.

BÖHME, M., DORR, M., MARTINETZ, T., AND BARTH, E. 2006. Gaze-contingent temporal filtering of video. In *Proceedings of the Eye Tracking Research & Applications Symposium (ETRA)*. ACM, San Diego, CA, 109–116.

ÇÖLTEKIN, A. 2006. Foveation for 3D visualization and stereo Imaging. Ph.D. thesis, Helsinki University of Technology, Helsinki, Finland. http://lib.tkk.fi/Diss/2006/isbn9512280175/.

CLARKE, J. H. 1976. Hierarchical geometric models for visible surface algorithms. *Comm. ACM 19*, 10, 547–554.

DALY, S., MATTHEWS, K., AND RIBAS-CORBERA, J. 2001. As plain as the noise on your face: Adaptive video compression using face detection and visual eccentricity models. *J. Elect. Imag. 10*, 1, 30–46.

DUCHOWSKI, A. T. AND ÇÖLTEKIN, A. 2007. Foveated gaze-contingent displays for peripheral LOD management, 3D visualization, and stereo imaging. *Trans. Multimedia Comput. Comm. Appl. 3*, 4, 1–18.

DUCHOWSKI, A. T., COURNIA, N., AND MURPHY, H. 2004. Gaze-contingent displays: A review. *CyberPsych. Behav. 7*, 6, 621–634.

FERWERDA, J. A., PATTANAIK, S. N., SHIRLEY, P., AND GREENBERG, D. P. 1996. A model of visual adaptation for realistic image synthesis. In *Proceedings of the 23rd Annual Conference Computer Graphics and Interactive Techniques (SIGGRAPH '96)*. ACM, New York, 249–258.

FOLEY, J. D., VAN DAM, A., FEINER, S. K., AND HUGHES, J. F. 1990. *Computer Graphics: Principles and Practice* 2nd Ed. Addison-Wesley, Reading, MA.

FUNKHOUSER, T. A. AND SÉQUIN, C. H. 1993. Adaptive display algorithm for interactive frame rates during visualization of complex virtual environments. In *Proceedings of the 20th Annual Conference Computer Graphics and Interactive Techniques (SIGGRAPH '93)*. ACM, New York.

GEISLER, W. S. AND PERRY, J. S. 2002. Real-time simulation of arbitrary visual fields. In *Proceedings of the Eye Tracking Research & Applications Symposium (ETRA)*. ACM, New York, 83–153.

GEISLER, W. S., PERRY, J. S., AND NAJEMNIK, J. 2006. Visual search: The role of peripheral information measured using gaze-contingent displays. *J. Vis. 6*, 9, 858–873.

GORDON, J. AND ABRAMOV, I. 1977. Color vision in the peripheral retina. II. Hue and saturation. *J. Optical Soc. Am. 67*, 2, 202–207.

HABER, R. N. AND HERSHENSON, M. 1973. *The Psychology of Visual Perception*. Holt, Rinehart, and Winston, Inc., New York.

HAHN, P. J. AND MATHEWS, V. J. 1997. Perceptually lossless image compression. In *Proceedings of the Data Compression Conference (DCC '97)*. IEEE Computer Society, Washington, DC, 442.

HAMADA, H. AND YUJIRI, A. 2004. Color Zone Map in peripheral vision at various illuminance levels. *Opt. Rev. 11*, 4, 240–248.

KOMOGORTSEV, O. AND KHAN, J. 2004. Predictive perceptual compression for real time video communication. In *Proceedings of the 12th Annual ACM International Conference on Multimedia (MULTIMEDIA '04)*. ACM Press, New York, 220–227.

LEVOY, M. AND WHITAKER, R. 1990. Gaze-directed volume rendering. In *Proceedings of the 17th Annual Conference Computer Graphics and Interactive Techniques (SIGGRAPH '90)*. ACM, New York, 217–223.

LOSCHKY, L. C. AND MCCONKIE, G. W. 2000. User performance with gaze contingent multiresolutional displays. In *Proceedings of the Eye Tracking Research & Applications Symposium (ETRA '00)*. ACM, New York, 97–103.

LOSCHKY, L. C. AND MCCONKIE, G. W. 2002. Investigating spatial vision and dynamic attentional selection using a gaze-contingent multi-resolutional display. *J. Exper. Psych. Appl. 8*, 2, 99–117.

LOSCHKY, L. C., MCCONKIE, G. W., YANG, J., AND MILLER, M. E. 2005. The limits of visual resolution in natural scene viewing. *Vis.Cogn. 12*, 6, 1057–1092.

LOSCHKY, L. C. AND WOLVERTON, G. S. 2007. How late can you update gaze-contingent multiresolutional displays without detection? *Trans. Multimedia Comput. Comm. Appl. 3*, 4, 1–10.

LUEBKE, D. AND ERIKSON, C. 1997. View-dependent simplification of arbitrary polygonal environments. In *Proceedings of the 24th Annual Conference Computer Graphics and Interactive Techniques (SIGGRAPH '97)*. ACM, New York.

MARTIN, P. R., LEE, B. B., WHITE, A. J. R., SOLOMON, S. G., AND RÜTTIGER, L. 2001. Chromatic sensitivity of ganglion cells in the peripheral primate retina. *Nature 410*, 933–936.

McConkie, G. W. and Loschky, L. C. 2002. Perception onset time during fixations in free viewing. *Behav. Res. Methods Instrum. Comput. 34*, 4, 481–490.

McConkie, G. W. and Rayner, K. 1975. The span of the effective stimulus during a fixation in reading. *Percept. Psychophys. 17*, 578–586.

Melloy, B. J., Das, S., Gramopadhye, A. K., and Duchowski, A. T. 2006. A model of extended, semi-systematic visual search. *Hum. Factors 48*, 3, 540–554.

Mullen, K. T., Sakurai, M., and Chu, W. 2005. Does L/M cone opponency disappear in human periphery. *Perception 34*, 7, 951–959. http://www.perceptionweb.com/perabs/p34/p5374.html.

Murphy, H. and Duchowski, A. T. 2001. Gaze-contingent level of detail. In *Proceedigns of the 2001 EuroGraphics Conference*. Springer, Berlin, Germany.

Murphy, H. and Duchowski, A. T. 2002. Perceptual gaze extent & level of detail in VR: Looking outside the box. In *Proceedings of the ACM SIGGRAPH Conference Abstracts and Applications (Sketches & Applications)*. ACM, New York.

Najemnik, J. and Geisler, W. S. 2005. Optimal eye movement strategies in visual search. *Nature 434*, 387–391.

Ohshima, T., Yamamoto, H., and Tamura, H. 1996. Gaze-directed adaptive rendering for interacting with virtual space. In *Proceedings of the 1996 Virtual Reality Annual International Symposium (VRAIS'96)*. IEEE, Washington, DC, 103–110.

O'Sullivan, C., Dingliana, J., Giang, T., and Kaiser, M. K. 2003. Evaluating the visual fidelity of physically based animations. *Trans. Graph. 22*, 3, 527–536.

Parkhurst, D., Culurciello, E., and Niebur, E. 2000. Evaluating variable resolution displays with visual search: Task performance and eye movements. In *Proceedings of the Eye Tracking Research & Applications Symposium*. ACM, New York, 105–109.

Parkhurst, D. J. and Niebur, E. 2002. Variable resolution displays: A theoretical, practical, and behavioral evaluation. *Hum. Factors 44*, 4, 611–629.

Parkhurst, D. J. and Niebur, E. 2004. A feasibility test for perceptually adaptive level of detail rendering on desktop systems. In *Proceedings of the Applied Perception, Graphics & Visualization Symposium (APGV'04)*. ACM, New York, 49–56.

Pellacini, F., Ferwerda, J. A., and Greenberg, D. P. 2000. Toward a psychophysically-based light reflection model for image synthesis. In *Proceedings of the 27th Annual Conference on Computer Graphics (SIGGRAPH '00)*. ACM, New York, 55–64.

Rasche, K., Geist, R., and Westall, J. 2005. Re-coloring images for gamuts of lower dimension. *Comput. Graph. Forum 25*, 3, 423–432.

Reddy, M. 2001. Perceptually optimized 3D graphics. *Comput. Graph. Appl. 21*, 5, 68–75.

Reingold, E. M., Loschky, L. C., McConkie, G. W., and Stampe, D. M. 2003. Gaze-contingent multi-resolutional displays: An integrative review. *Hum. Factors 45*, 2, 307–328.

Sakurai, M., Ayama, M., and Kumagai, T. 2003. Color Appearance in the entire visual field: Color zone map based on the unique hue component. *J. Opti. Soc. Am. A. 20*, 11, 1997–2009. http://www.opticsinfobase.org/abstract.cfm?URI=josaa-20-11-1997.

Shebilske, W. L. and Fisher, D. F. 1983. Understanding extended discourse through the eyes: How and why. In *Eye Movements and Psychological Functions: International Views*, R. Groner, C. Menz, D. F. Fisher, and R. A. Monty, Eds. Lawrence Erlbaum Associates, Hillsdale, NJ, 303–314.

Solomon, S. G., Lee, B. B., White, A. J. R., Rüttiger, L., and Martin, P. R. 2005. Chromatic organization of ganglion cell receptive fields in the peripheral retina. *J. Neurosci. 25*, 18, 4527–4539.

Tobii Technology Ab. 2003. Tobii ET-17 Eye-tracker Product Description (v1.1). http://www.tobii.se/.

Vince, J. A. 1995. *Virtual Reality Systems*. Addison-Wesley, Reading, MA.

Watson, B., Walker, N., and Hodges, L. F. 2004. Supra-threshold control of peripheral LOD. *Trans. Graphics 23*, 3, 750–759.

Watson, B., Walker, N., Hodges, L. F., and Worden, A. 1997. Managing level of detail through peripheral degradation: Effects on search performance with a head-mounted display. *ACM Trans. Comput. Hum. Interact. 4*, 4, 323–346.

Wolfe, J. M. 1994. Wolfe, J. M. 1994. Guided search 2.0: A revised model of visual search. *Psychonomic Bull. Rev. 1*, 2, 202–238.

Wyszecki, G. and Stiles, W. S. 1982. *Color Science: Concepts and Methods, Quantitative Data and Formulae* 2nd Ed. John Wiley & Sons, New York.