Severe Loss of Tritan Color Discrimination in RPE65 Associated Leber Congenital Amaurosis

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PURPOSE. RPE65-associated Leber congenital amaurosis (RPE65-LCA) is a progressive severe retinal dystrophy with early profound dysfunction of rod photoreceptors followed by progressive cone photoreceptor degeneration. We aim to provide detailed information about how cone dysfunction affects color discrimination.

METHODS. Seven adults (aged 16–21) with RPE65-LCA underwent monocular color discrimination assessment using the Trivector and Ellipse versions of three computerized tests: Cambridge Colour Test (CCT), low vision version of the Cambridge Colour Test (lvCCT), and the Universal Colour Discrimination Test (UCDT). For comparison, subjects were also tested using the American Optical Hardy Rand Rittler (AO-HRR) plates. Each assessment was repeated three times.

RESULTS. The Trivector version of the tests demonstrated that color discrimination along the tritan axis was undetectable in four subjects, and severely reduced in three subjects. These findings were confirmed by the Ellipse version of the tests. Color discrimination along the proton and deutan axes was evident but reduced in six of seven subjects. Four of seven subjects were unable to read any of the HRR plates.

CONCLUSIONS. The computerized color vision tests adopted in this study provide detailed information about color discrimination in adult RPE65-LCA patients. The condition is associated with severe impairment of color discrimination, particularly along the tritan axis indicating possible early involvement of S-cones, with additional proton and deutan loss to a lesser extent. This psychophysical assessment strategy is likely to be valuable in measuring the impact of therapeutic intervention on cone function.

Keywords: color vision, retina, Leber congenital amaurosis, LCA, LCA2, clinical trials, endpoints

Lever congenital amaurosis (LCA) is thought to affect between 1 in 33,000 to 1 in 81,000,1,2 and is believed to account for ≥5% of all inherited retinal diseases.3 Presentation is from birth with severe visual impairment, nystagmus, and poor pupillary responses. While LCA is known to be progressive in nature, this can vary widely among patients. To date, 25 genes have been identified to account for approximately 70% to 80% of cases, with RPE65-associated LCA accounting for approximately 5% to 10%.5 RPE65 encodes a retinoid isomerase expressed in the RPE and is a critical component in the visual cycle. Following successful gene replacement in RPE65 canine4 and murine models5, human gene therapy trials have demonstrated safety and varying levels of efficacy.6–10

Subjects with RPE65-LCA have reduced or absent rod function and reduced cone-driven temporal sensitivity.11,12 However, to date, little is known about how these deficiencies affect color vision in RPE65-LCA. Jacobson et al.13 noted absence of S-cone function in all of the 6 assessed RPE65-LCA patients. This group further describes residual L-cone function in two other RPE65-LCA patients.15 Lorenz et al.16 also noted poorer sensitivity to blue light (mediated by S-cones) than red light (mediated by L-cones) in RPE65-LCA patients. While Paunescu et al.15 described residual color vision, but difficulty in blue-green discrimination, in four RPE65-LCA children. However, further description or quantification of color discrimination has not been made to date. This may be due in part to limitations of traditional color vision assessments, as described below.

Of the three cone classes, S-cones account for a significant minority (<10%) of the cone population. Furthermore, they are absent at the foveal center16 and constitute 5.7% ± 0.7% of the photoreceptor mosaic imaged in vivo approximately 1° from fixation,17 suggesting a more peripheral placement of this already infrequent cone class. Interestingly, M- and L-cones share many physiologic and genetic similarities, and considerable variability in the L:M-cone ratio has been identified in subjects with normal vision.18

Many different tests exist to assess color vision; they typically use a test stimulus of a defined chromaticity, which is compared with a reference stimulus of a different chromaticity. Pseudoisochromatic plate tests are most often used in clinical care and are based on the principles of Stillig,19 where stimuli are presented on a background, with both being made...
up of discrete discs that vary in size and luminance. This ensures that the object is only identifiable from its background by its chromatic difference and not from a difference in perceived luminance. Computerized color vision testing is less frequently used in clinical practice and more so in research settings. Computerized tests such as the Colour Assessment and Diagnosis test (CAD),\textsuperscript{20} the Cambridge Colour Test (CCT),\textsuperscript{21} the low-vision version of the Cambridge Colour Test (lvvCCT),\textsuperscript{22} and the Universal Colour Discrimination Test (UCDT)\textsuperscript{23} offer multiple advantages. Firstly, through using methods described below, they allow greater quantitative characterization of color discrimination. Secondly, by incorporating the "chromatophotometer,"\textsuperscript{24} computerized color tests change the chromatic difference between the stimulus and the background in response to patient performance, enabling more precise measurement of color discrimination. Moreover, they are able to randomize the presentation of stimuli to counteract any learning effect.

The CCT was the first popular computerized test to measure color discrimination.\textsuperscript{21} The CCT has been since shown to be suitable only for patients with a visual acuity lower, and thereby better, than 0.78 LogMAR.\textsuperscript{23} Identifying the limitation of poor visual acuity in assessing color discrimination, a modified version of the CCT, the lvvCCT, was developed.\textsuperscript{22} Subsequently, the UCDT was established and shown to accurately measure color discrimination in both adults and children, even with a visual acuity higher, and thereby worse, than 1.00 logMAR.\textsuperscript{25}

There are two versions of each computerized test: the Trivector version and the Ellipse version. Both versions measure the amount of saturation required to discriminate a color target from a series of gray distractors. The Trivector version is a screening version because it allows rapid testing of color discrimination along three vectors; namely the protan, deutan, and tritan confusion axes. Figure 1A shows the saturation thresholds obtained from an ideal observer with normal color discrimination, with a saturation threshold of 5.43, 2.44, and 7.29 in the protan, deutan, and tritan confusion axes, respectively. The Ellipse version, shown in Figure 1B, assesses color discrimination along more than three confusion axes, which allows an Ellipse to be determined.\textsuperscript{25}

In this study, we aim to provide detailed information about how cone dysfunction in RPE65-LCA affects color vision by using the American Optical Hardy Rand Rittler (AO-HRR) plate test and three computerized color discrimination tests: the CCT, lvvCCT, and UCDT. The AO-HRR plate test was used for comparison, as such plate tests are commonly used in a clinical setting, while, the computerized tests were chosen as they have been shown to be effective in testing subjects with inherited or acquired color vision defects, including subjects with low vision.\textsuperscript{22,23,26–28}

**METHODS**

**Subjects**

Seven subjects (aged 16–21) were each molecularly confirmed as having two likely disease-causing sequence variants in RPE65 following targeted next generation sequencing of the coding regions of 176 retina-associated genes from genomic DNA extracted from peripheral blood leukocytes (performed at The Manchester Centre for Genomic Medicine, Manchester, UK). Parental blood was used to confirm the variants to be in trans by cosegregation analysis with Sanger direct sequencing, where possible. The L-/M-opsin genes were not screened. The study protocol adhered to the tenets of the Declaration of Helsinki and was approved by the Moorfields Eye Hospital Ethics Committee. Informed consent was obtained from all subjects prior to entering the study.

**Assessments of Color Discrimination**

All patients were assessed monocularly, with their current spectacle correction where used, using the AO-HRR chart first and then with the three computerized tests in a randomized fashion. Furthermore, the first eye tested was also randomized and all patients were instructed using standardized text instructions, specific for each individual assessment. The
instructions asked the patient to identify the stimulus as compared with the gray background or gray distractors (as appropriate) and provide a response using the response box. If they could not see the stimulus or a difference, subjects were asked not to respond. A demonstration test was performed binocularly for each test, to ensure that the subject had understood the instructions. For each test, the Trivector version was run first for each eye independently, followed by the Ellipse version. The Ellipse version assessed color discrimination along a subset of 10 axes equally spaced every 36°. The neutral points of each computerized test are reported in Table 1.

Each computerized test aimed to measure the minimum saturation required by the subject to discriminate the colored target from the gray background or the gray distractors. On each trial, if the observer responded correctly, the saturation of the target would decrease. Conversely, if they answered incorrectly the saturation of the target would increase. The tests used a weighted 1 up/1 down staircase with an up/down ratio of 1/3 in order to converge on the 75% threshold. The step size used depended on the number of reversals completed. To begin with, the saturation was equal to the maximum length of the current axis that was within the color gamut of the monitor and the decreasing rate of the step size was 48% until the first reversal and 8% for the remaining reversals. The increasing rate of the step size was always 24%. The staircase consisted of six reversals and the mean of the last four reversals was taken as the threshold. More details on the adaptive method used can be found in Regan et al.21

Of note, a nonresponse was considered to be an incorrect response. If the test recorded five consecutive incorrect responses the staircase along that particular axis would terminate, with the intention to shorten testing time in those unable to discriminate a particular hue even at its maximum saturation. In this case, the staircase along that hue/axis would terminate after the first five incorrect responses instead of continuous, unnecessary, testing to achieve the required number of reversals.

The AO-HRR Plate Test score was set as the number of complete plates identified out of the 14 diagnostic plates (numbered 11–24).

Each patient underwent the above assessments of color discrimination three times on different days. The above tests took approximately 2 hours to complete (further to any breaks required by the patient), with the three sessions being performed over a range of 4 days to 11 weeks.

**Table 1. Neutral Points of Three Computerized Color Tests**

<table>
<thead>
<tr>
<th></th>
<th>CCT</th>
<th>lvvCCT</th>
<th>UCDT</th>
</tr>
</thead>
<tbody>
<tr>
<td>u'</td>
<td>0.1977</td>
<td>0.1977</td>
<td>0.211</td>
</tr>
<tr>
<td>v'</td>
<td>0.4689</td>
<td>0.4689</td>
<td>0.4735</td>
</tr>
</tbody>
</table>

**Stimuli**

**Low-Vision Version of the Cambridge Colour Test (lvvCCT).** In this assessment, four discs are presented on a 2-CD/m² neutral background in a diamond-shaped array. Each subtends 4° at the test distance (1.5 m) and was separated by 2.5° from the adjacent discs. On each presentation, one of the discs differs in chromaticity from the remaining three (which remain of neutral hue) and the patient was asked to identify which of the four discs is different in color.22

**Cambridge Colour Test (CCT).** The CCT involves the presentation of a 5° Landolt C-like ring in four orientations, against a background that differs in chromaticity only. Based on the principles of Stillings,19 the target and background are made up of many discrete discs, each with its own contour, and the luminance of the individual discs are randomized. These two maneuvers allow discrimination of the target from the background using chromaticity alone. The observer was instructed to report the position of the 1° gap in the C-like ring presented.21

**Universal Colour Discrimination Test (UCDT).** The UCDT is a two alternative forced-choice assessment involves the presentation of circles of random luminance. A subset of circles delineates a 8.58° square stimulus that varies in saturation and hue only, on the left or right hand side of the screen, with the patient being asked to distinguish the laterality.25

**Assessment of Best-Corrected Visual Acuity**

Each patient underwent a subjective refraction and subsequent assessment of BCVA. The number of Early Treatment Diabetic Retinopathy Study (ETDRS) letters read was scored. This was performed three times, on different days, and the number of ETDRS letters read was averaged and converted into a logMAR equivalent.

**Statistical Analysis**

Statistical analyses were performed using the Stata statistical software package (StataCorp, College Station, TX, USA). For Trivector assessment of the three computerized tests, a one-way repeated measures ANOVA was used to investigate any statistically significant difference in the mean saturation threshold between the three (proton, deutan, and tritan) confusion axes. In cases where a statistically significant difference was found, a post hoc pairwise comparison with Bonferroni correction was used to compare the mean saturation thresholds between the (1) proton and deutan, (2) proton and tritan, and (3) deutan and tritan axes, respectively. To minimize the clustering effect of using data from both eyes, only results from the right eye of all subjects were analyzed.
The same statistical analysis was performed on data from the left eye and provided comparable results.

**RESULTS**

Table 3 shows the demographics, RPE65 variants, and average BCVA for all seven subjects.

**AO-HRR Test**

Only three subjects (subjects number 4, 5, and 6) were able to read at least one full plate. The total number of plates read by these three subjects ranged from one to six. Of note, the plates read were distributed equally throughout the deutan, protan, tritan, and tetartan plates. A normal trichromat should be able to identify all 14 diagnostic plates.

**Low-Vision Version of the Cambridge Colour Test (lvvCCT): Trivector Test**

Figure 2 shows the mean saturation threshold and standard error of each eye, of each patient in the protan, deutan, and tritan axes, as calculated by the Trivector assessment of the lvvCCT. As described above, a normal trichromat has a saturation threshold of less than 10 (shown by the gray shaded area in each row in Fig. 2). The maximum saturation threshold the monitor is able to present is 110 in each axis (as shown by the dotted line in each row in Fig. 2).

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Sex</th>
<th>Age</th>
<th>RPE65 Variant 1</th>
<th>RPE65 Nucleotide 1</th>
<th>RPE65 Variant 2</th>
<th>RPE65 Nucleotide 2</th>
<th>Right Eye BCVA</th>
<th>Left Eye BCVA</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>Female</td>
<td>21</td>
<td>c.118G&gt;A</td>
<td>p.Gly40Ser</td>
<td>c.955G&gt;A</td>
<td>p.Glu319Lys</td>
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<td>0.4</td>
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<tr>
<td>2</td>
<td>Female</td>
<td>20</td>
<td>c.989G&gt;A</td>
<td>p.Cys330Tyr</td>
<td>c.143_1445delAGA</td>
<td>p.Glu143_1445delAGA</td>
<td>0.7</td>
<td>0.7</td>
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<tr>
<td>3</td>
<td>Male</td>
<td>20</td>
<td>c.1451G&gt;A</td>
<td>p.Gly484Asp</td>
<td>c.1451G&gt;A</td>
<td>p.Glu484del</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>4</td>
<td>Female</td>
<td>20</td>
<td>c.11+5G&gt;A</td>
<td>Splice region</td>
<td>c.1341_1342dupCT</td>
<td>p.Cys448SerfeTer4</td>
<td>0.8</td>
<td>0.7</td>
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<tr>
<td>5</td>
<td>Female</td>
<td>19</td>
<td>c.1078C&gt;T</td>
<td>p.Pro363Thr</td>
<td>c.1078C&gt;T</td>
<td>p.Pro363Thr</td>
<td>0.6</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>Male</td>
<td>18</td>
<td>c.370C&gt;T</td>
<td>p.Arg124Ter</td>
<td>c.952T&gt;A</td>
<td>p.Arg837Asn</td>
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<td>0.5</td>
</tr>
<tr>
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<td>Male</td>
<td>16</td>
<td>c.11+5G&gt;A</td>
<td>Splice region</td>
<td>c.245G&gt;A</td>
<td>p.Arg821Lys</td>
<td>0.7</td>
<td>0.6</td>
</tr>
</tbody>
</table>

* Sequence variants preceded with an asterisk are noted to be novel.
Four participants (subjects 1, 2, 3, and 7) were unable to see the stimulus in the tritan axis despite presentation of a maximally saturated stimulus (Fig. 2). Conversely three participants (subjects 4, 5, and 6) were able to identify the tritan stimulus below the maximal threshold, suggesting that these participants had some color discrimination in the tritan axis. Given that these saturation threshold values are close to the maximal level, their tritan discrimination can be described as poor. Interestingly, when reviewing the same in the protan and deutan axes, all participants, except subject 7, exhibited varying degrees of color discrimination in the protan and deutan axes.

**Figure 2.** Low vision version CCT Trivector test results. Shown are the mean (symbols) and one standard error (vertical bars) of the mean saturation along the tritan (blue), deutan (green), and protan (red) axes, for each eye of each of the seven tested subjects. The dotted line in each row represents the maximum saturation threshold the monitor is able to present (110). The gray shaded area in each row corresponds to the normal trichromatic range (0–10).

**Figure 3.** CCT Trivector test results. Shown are the mean (symbols) and one standard error (vertical bars) of the mean saturation along the tritan, deutan, and protan axes, for each eye of each of the seven tested subjects. The dotted line in each row represents the maximum saturation threshold the monitor is able to present (110). The gray shaded area in each row corresponds to the normal trichromatic range (0–10).
There was a statistically significant difference ($F_{(2,12)} = 11.42, P = 0.0017$) in mean saturation threshold between the three confusion axes, suggesting a difference in color discrimination between the three confusion axes. A Bonferroni post hoc test identified subjects to have a significantly better mean saturation threshold in the protan axis (39.44 ± 9.15, $P = 0.003$) and the deutan axis (36.02 ± 9.15, $P = 0.006$) as compared with the tritan axis. This suggests significantly worse color discrimination in the tritan axis as compared with the protan and deutan axes.

Cambridge Colour Test (CCT): Trivector Test

Figure 3 illustrates the mean saturation threshold and standard error of each eye, of each patient in the protan, deutan, and tritan axes as calculated by the Trivector assessment of the CCT. Subjects 2, 3, 6, and 7 showed no evidence of color discrimination, using the CCT trivector test, as indicated by the maximum possible saturation thresholds. Subjects 1 and 5 showed evidence of color discrimination along the deutan and protan confusion axes. Subject 4 appeared to retain color discrimination along all three confusion axes, with a markedly variable performance in the deutan axis of the right eye (as indicated by the respective error bars).

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Universal Colour Discrimination Test (UCDT): Trivector Test

Figure 4 shows the mean saturation threshold and standard error of each eye, of each patient in the protan, deutan, and tritan axes as calculated by the Trivector assessment of the UCDT. Subject 4 exhibited discrimination in all three confusion axes in both eyes, but as shown by the error bars (Fig. 4), this patient’s responses were very variable in four of the six axes tested over the two eyes. Of the remaining six subjects, only subject six demonstrated residual tritan discrimination (left eye), which was both variable and at a level close to the maximum threshold the monitor is able to present. Furthermore, of these six subjects, two (subjects 3 and 5) demonstrated discrimination in the protan and deutan axes.

In keeping with the CCT Trivector results, statistical analysis did not show a statistically significant difference in the mean saturation threshold between the three axes ($F_{(2,12)} = 0.63, P = 0.551$).

CCT, LvvCCT, and UCDT Ellipse Test

The subset of 10 saturation thresholds identified using the Ellipse test were fitted with a ‘best-fit’ Ellipse using a least-square procedure. This allows color discrimination to be described using three parameters; the orientation of the Ellipse, the axial ratio (the ratio between the major and minor axes), and the area within the Ellipse. Each parameter allows quantification of a different aspect of color discrimination. The orientation of the Ellipse provides information regarding the axes in which the patient lacks discrimination and can suggest loss of tritan, protan, or deutan discrimination if it correlates with these confusion axes: the greater the axial ratio, the more selective the loss of color discrimination in the relevant confusion axis. The area within the Ellipse can provide a quantification of the discrimination ability of the patient: the smaller the area the better the color discrimination ability. Color discrimination Ellipses of a normal trichromat have an axial ratio and area within the Ellipse typically less than 2 and 340 (using a 10^3 unit multiplication in keeping with previously published and accepted methods), respectively.

Figure 5 shows the mean and standard error of the areas of the best-fit color discrimination Ellipse for each test. Furthermore, the dashed line represents the maximum threshold the
monitor is able to present. Figure 5 confirms that color discrimination can be measured, with differing variability in six of the seven patients; however, subject 7 demonstrated very poor color discrimination with all three tests. The LvvCCT had a lower average Ellipse area in five of the remaining six tested subjects than the other two tests, suggesting that these patients had better color discrimination when assessed with the LvvCCT, as compared with either the CCT or UCDT; the

![Figure 5. Color discrimination Ellipse areas. Shown are the mean (symbols) and one standard error (vertical bars) of the area of the Ellipse for the LvvCCT, CCT, and UCDT, for each eye of each of the seven tested subjects. The dotted line represents the maximum saturation threshold the monitor is able to present. A normal trichromatic region is from 0 to 340.](image)

![Figure 6. Color discrimination Ellipse axis orientation. Shown are the mean (symbols) and one standard error (vertical bars) of the axes of the Ellipse for the LvvCCT, CCT, and UCDT, for each eye of each of the seven tested subjects. The corresponding deutan (green), tritan (blue), and protan (red) confusion axes are also shown.](image)
where S-cone loss is seen prior to L- and M-cone loss.36,37
be found from studies in dog and mouse models of
more severely in the progressive cone dysfunction seen in
pigment than L- and M- cones, and hence affected earlier and
color discrimination, we suggest the lvvCCT to be a more
suitable color vision assessment, as compared with the CCT
and UCDT, in this cohort of RPE65-LCA adults.
This study demonstrates that color vision can be quantified
in most RPE65-LCA subjects. Through using appropriate
assessments of color vision, we have identified that these
subjects have a severe loss of tritan color discrimination, prior
to loss of protan or deutan discrimination. This suggests that S-
cone function is lost earlier in the natural history of RPE65-LCA
compared with L- and M-cones. Gene therapy for RPE65-LCA
has been shown to be safe with varying levels of efficacy and
durability noted in both phase I/II and III studies.5-10,38
Subsequently, multiple new clinical trials are currently
underway to investigate potential benefits of gene therapy.
Therefore, in-depth assessments of visual function are becom-
ing more critical. Furthermore, knowledge and sensitive
assessments of color discrimination are valuable tools in the
measurement of the impact of intervention on cone function,
both to accurately describe change and to inform patient
experience.

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