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EYE TRACKING APPLICATIONS IN COLOUR VISION ASSESSMENT

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Traditionally, colour vision assessment relies on the patient's subjective response. The current study introduces an objective approach using eye movement analysis to explore the perception of moving chromatic stimuli. Chromatic sensitivity was assessed using Dynamic-Static Colour Vision Test (DSCVT) stimuli. A total of 20 (15 female and 5 male) participants (aged 18–28 years, 21.7 ± 2.2) were recruited for the study. During stimulus presentation, participants were instructed to focus on the chromatic stimuli and provide a subjective response at the end of the demonstration. Simultaneously, eye gaze coordinates were recorded to assess chromatic sensitivity objectively.

Sensory thresholds were determined using the method of constant stimuli, with detection probabilities computed through psychometric function fitting. Smooth pursuit eye movements were analysed using algorithms developed by Larsson et al. [1] and Nyström et al. [2], enabling the objective identification of the direction in which tracking distance was the longest. Higher chromatic saturation increased smooth pursuit detection; however, inconsistencies in individual performance prevented consistent modelling of the psychometric function due to response variability. In cases where stimulus intensity exceeded threshold levels, correct responses were often given without tracking the object, limiting smooth pursuit-based assessment. Smooth pursuit movements alone were insufficient for severity classification of colour vision deficiencies; further research is needed using additional eye movement metrics.

Keywords: *Objective colour vision assessment, smooth pursuit*

1. INTRODUCTION

Red-green colour vision deficiencies affect approximately 0.5 % of women and up to 8 % of men [3]. The ability to accurately differentiate between coloured stimuli with varying spectral properties is particularly important for professionals in the transport sector, medical practitioners, graphic designers, and children, as colour codes play a significant role in educational processes and can affect job performance later in life [4]–[6].

Traditionally, red-green colour deficiencies have been diagnosed using psychophysical methods that rely on an individual's subjective response. Clinical assessment is mainly performed by applying different tests available in practice (e.g., Ishihara test, Farnsworth–Munsell test, Cambridge Colour Test, Hardy–Rand–Rittler test and different online tests) all of which rely on the subjective response of the patient. However, since the units of the reported data are different, the results obtained by different tests cause difficulties with the interpretation of the severity of red-green colour deficiency, as well as comparing the results between the tests [7].

Recent technological advancements have proposed objective identification of red-green deficiencies through DNA analysis [8]. DNA analysis method assesses whether an individual's genetic code contains the necessary information for normal L and M cone photopigments, which are essential for perceiving colours within the medium and long wavelength ranges of visible light. While the test proposed by Davidoff et al. is based on the underlying pathobiology of colour vision deficiencies and can aid in determining whether the observed colour deficiencies are inherited or arise from other causes, its complexity limits applicability in clinical screening settings, not to mention as a screening method for detecting colour vision deficiencies [8]. Objective colour vision testing has also been proposed by Zheng et al. (2021) by inducing visual evoked potentials (VEPs) and recording electroencephalography signals [9]. The results have demonstrated a significant correlation between the results of FM-100 hue test and the SSVEP colour vision severity index developed by the authors. However, the effectiveness of SSVEPs is affected by the frequency detection accuracy and long calibration period, which make the clinical applications of this method more complicated and subject to the skills of the test operator [10].

The rapid advancement of eye tracking technologies, coupled with the increasing availability of compact and user-friendly devices, has paved the way for their integration into objective assessments of visual functions such as contrast sensitivity [11], [12] and visual field performance [13]. A particularly compelling example is provided by Taore et al. (2020), who demonstrated that eye movement analysis can effectively classify cases of red-green color vision deficiency. Their approach achieved impressive diagnostic accuracy – 90.9 % sensitivity and 91.3 % specificity – in differentiating individuals with normal colour vision, deuteranopia, and protanopia, while offering insights into the severity of colour vision deficiencies [14]. It is important to note that their classification success was based on a distinct experimental paradigm involving grating stimuli and the analysis of optokinetic nystagmus (OKN), which differs fundamentally from

the smooth pursuit-based methodology employed in the present study.

The current study explores the application of eye tracking as an objective method for determining chromatic sensitivity thresholds. By applying algorithms for smooth pursuit detection, it investigates whether eye movement analysis can be used not only to classify different types of colour vision deficiencies, but also to objectively quantify perceptual thresholds across all deficiency types [1], [2], [15]. This approach bridges the gap left by SSVEP and genetic testing by offering a functional, behaviour-based measure of chromatic sensitivity through dynamic stimulus tracking.

2. METHODOLOGY

2.1. Participants

The study included 20 participants (5 male, 15 female) aged 18 to 28 years (mean age: 21.7 ± 2.2 years). All participants exhibited visual acuity of no less than 0.8 (decimal units) across both near and distance conditions, either unaided or corrected with contact lenses. Binocular vision was confirmed in all participants via the Worth test, and the HRR test revealed no colour vision deficiencies. Participants also reported no history of ocular disease. Prior to enrolment, the aims of the research and all examination procedures used during the experimental sessions were thoroughly explained to the participants. The study was conducted in accordance with the Declaration of Helsinki and received approval from the Ethics Committee of the Department of Optometry and Vision Science at the University of Latvia (29 January 2025).

2.2. Test Stimulus

Eye movement recording was performed with EyeLink 1000+ video-oculograph (SR Research, Canada) at a frequency of 1000 Hz. Stimuli were presented on a BenQ computer screen (53.3 x 30 cm; 1920 x 1080 px) at a distance of 140 cm. Colour vision was assessed with DSCVT colour vision test stimuli [16]. The background size of the test stimulus was 10.41 degrees of visual field, the size of the coloured stimulus was 1 degree of visual field. The coloured stimuli moved at a speed of 4.47 degrees per second in one of 4 directions: right or left, up or down. Within the framework of this study, chromatic sensitivity was assessed in three directions in the CIExy colour space, corresponding to 351.77, 326.67 and 246.07 degrees.

2.3. Examination Procedure

Stimuli were presented along three chromatic directions – protan (351.77°), deutan (326.67°), and tritan (246.07°) – at seven equally spaced saturation levels specific to each direction. It was assumed that the maximum stimulus saturation in the protan, deutan, and tritan directions within the CIExy colour space is twice as high as the threshold values corresponding to the norm in the Cambridge Colour Test (CCT). Specifically, the maximum saturation values were set at 0.025, 0.025, and 0.04 xy' units, respec-

tively. The colour coordinates of the stimuli were selected to ensure that they were evenly spaced along each of the confusion lines within the designated intervals. During the stimulus demonstration, participants were instructed to follow the moving coloured test stimulus. After the demonstration, they were asked to press the corresponding button on the keyboard to indicate the direction of movement of the coloured stimulus. To determine the chromatic sensitivity thresholds in each colour direction, the constant stimulus method was employed. Each test stimulus was presented 20 times, resulting in a total of 140 stimuli for each participant in each colour direction. Given that the examinations were conducted in three colour directions and that the tritan direction included two different test stimulus sizes (1 and 0.5 degrees of visual angle), a total of 560 test stimuli were presented during the experimental session in random order.

2.4. Threshold Estimation

Chromatic sensitivity thresholds were estimated by fitting a logistic model to participants' responses, constrained between 25 % and 100 % detection probability to account for random guessing. This approach facilitated the determination of the saturation level at which chromatic stimuli became reliably detectable. The psychometric function was modelled using a logistic equation, with a lower bound of 25 % (reflecting chance-level performance) and an upper bound of 100 % (perfect detection). Threshold and slope parameters were estimated by maximizing the likelihood function, using the Nelder–Mead optimisation algorithm [17]. Initial parameter estimates were obtained by fitting the experimental data with a linearized form of the logistic function using linear regression. Final values were refined using the Nelder–Mead algorithm, iterating until the change in likelihood between the best and worst apex reflections fell below 0.01%.

3. EYE TRACKING DATA PROCESSING

In the present study, the processing of eye movement data involved several stages: (1) identifying and removing blink events, (2) calculating eye movement speed, (3) detecting and eliminating artefacts based on speed, (4) determining individual saccade threshold values, (5) identifying saccades, (6) analysing inter-saccade intervals, (7) detecting smooth pursuit movements and determining their direction, and, finally, (8) assessing the objective response of the participant (see Fig. 1). When a missing signal was detected (blink event), the first local minimum of the y-coordinate of the eye gaze was identified both before and after the specified interval, as described by Larsson et al. [15]. Changes in eye gaze velocity were computed using a Savitzky-Golay filter with a window width of 11 units – five entries on either side of each point – assuming a second-order polynomial approximation. The first-order derivative of the SG filter was utilised to calculate velocity values for eye gaze positions along the x and y axes. Angular velocity was determined by computing speed along the x and y axes and scaling the results to account for computer monitor

parameters and viewing distance.

Before proceeding with further analysis, it was essential to check whether the eye movement recording data contained velocity values exceeding the maximum possible eye movement velocity of 1000 deg/s. Initially, eye movement velocity peaks exceeding the threshold were identified. Subsequently, the first local minimum was determined to the right and left of each local velocity peak that exceeded 1000 deg/s. The data set lying between local minimum values was excluded from further analysis. In regions free from blink and velocity artefacts, individual threshold values for saccade onset and offset were calculated, as outlined by Nyström and Holmqvist [18]. A saccade was detected if the onset threshold exceeded 30 deg/s, based on the individual speed thresholds for saccade onset and offset. Additionally, the presence of a post-saccadic glissade was evaluated; if a glissade followed a saccade, the corresponding regions were merged into a single entity.

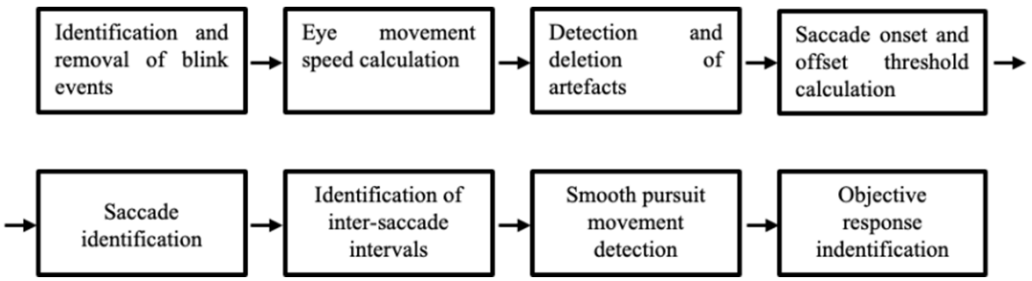

Fig. 1. Data processing pipeline for detecting smooth pursuit direction from eye gaze recordings.

Smooth pursuit movements were identified in the intervals between successive saccades when the duration of inter-saccadic intervals exceeded 40 ms. Smooth pursuit movements were determined using the algorithm proposed by Larsson et al. (2015) [1]. In the initial step of the analysis, the method tested whether successive eye gaze position coordinates, sampled at 20 ms intervals via the Relay method, aligned with a specific direction. It was assumed that subsequent intervals overlapped by 6 ms. When the Relay test value fell below 0.01, it was interpreted that the points within the interval represented a single direction. The next step involved merging consecutive intervals with a Relay test value of less than 0.01 (see Fig. 2). If the length of the combined intervals exceeded 40 ms, the resulting areas were subjected to principal component analysis (PCA) to identify the direction with the greatest dispersion of eye gaze coordinates. Based on the PCA results and descriptive parameters for eye gaze coordinates associated with a specific interval, the interval was assessed for instances of smooth pursuit. Larsson et al. (2015) suggest that smooth pursuit movements can be identified when four specific criteria are met [1]. However, in this study, smooth pursuit movements were also recognised in cases where the length of the smooth pursuit did not reach 1.9 degrees of the visual field, provided that the other criteria were satisfied.

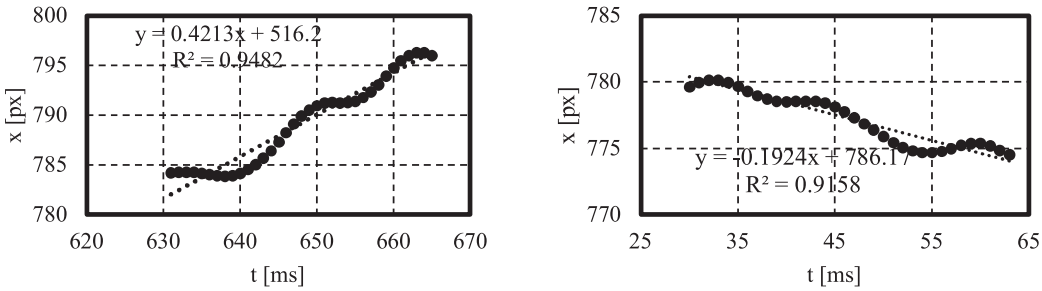

Fig. 2. The plots on the left and right illustrate eye-tracking coordinates corresponding to instances of smooth pursuit movements.

4. OBJECTIVE RESPONSE DETERMINATION

To objectively evaluate the direction of eye gaze associated with smooth pursuit movements, a linear regression analysis was conducted on the x and y coordinates of eye gaze, specifically for cases where the first three criteria were met. If the absolute value of the slope coefficient of the linear regression equation was less than 1 ($|slope| < 1$), it was concluded that the tracking movement primarily occurred in the horizontal direction; otherwise, it was classified as vertical movement. To further differentiate between horizontal movements to the right or left, and vertical movements up or down, separate linear regression analyses were performed on the time values corresponding to the x coordinates and the time values corresponding to the y coordinates. A positive slope coefficient for horizontal movement indicated movement to the right, while a negative slope coefficient indicated movement to the left. For vertical movement, a positive slope coefficient indicated upward movement, whereas a negative slope coefficient indicated downward movement. The objective response to the stimulus was assessed by calculating the direction of gaze that covered the longest total distance during the stimulus presentation.

5. RESULTS

5.1. Subjectively Estimated Chromatic Sensitivity Thresholds

After conducting a comprehensive analysis of the subjective responses of participants, it was determined that, in most cases, the direction of motion was accurately identified across all three axes of colour space, regardless of saturation level. Errors were primarily observed with a limited number of less saturated test stimuli, which hindered the precise evaluation of chromatic sensitivity thresholds. When assessing chromatic sensitivity using tritan-type stimuli with a size of 0.5 degrees of visual angle, more characteristic responses were noted; specifically, the number of correct answers increased as stimulus saturation increased. Our analysis

suggests that chromatic sensitivity thresholds along the tritan axis, measured with stimuli of 0.5 degrees, ranges from 0.0121 to 0.0205, which aligns with previous findings (see Fig. 3). However, in the case of two individuals, threshold values were identified that exceeded the statistically average norm by factors of 1.83 and 1.85. Consequently, these participants were excluded from further analysis. A comparison of the tritan results with stimulus sizes of 0.5 and 1 degree confirms that stimulus size significantly affects performance in the colour vision test, primarily due to the reduced light intensity on the retina. Similar findings were reported in the study by Barbur et al. (2016), which demonstrated a statistically significant increase in chromatic sensitivity thresholds when test stimuli were reduced to sizes below 1.1 deg² [19].

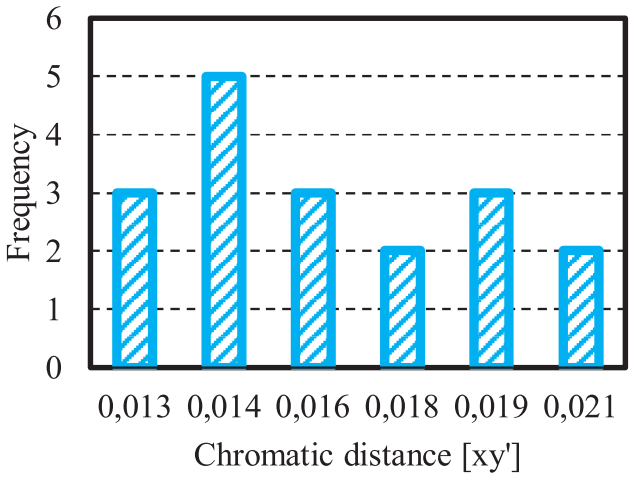

Fig. 3. Chromatic sensitivity thresholds measured along the tritan axis in colour space using a test stimulus with a size of 0.5 degrees.

6. OBJECTIVELY ESTIMATED CHROMATIC SENSITIVITY THRESHOLDS

To objectively assess chromatic sensitivity during the experimental session, participants were instructed to follow coloured stimuli while their eye gaze was recorded. The objective analysis of eye movements during the presentation of the stimuli suggests that as the saturation of the stimuli increases, the likelihood of smooth eye pursuit movements aligning with the direction of the stimulus also increases. However, the experiment revealed that smooth pursuit movements were detected less than 50 % of the time when suprathreshold coloured stimuli were presented. In the deutan and protan colour directions, a moderately high correlation was observed between chromatic stimulus saturation and the direction of stimulus motion. In contrast, in the tritan colour direction, a strong correlation was found between stimulus saturation and the frequency of correctly identified motion direction for both stimulus sizes (see Fig. 4).

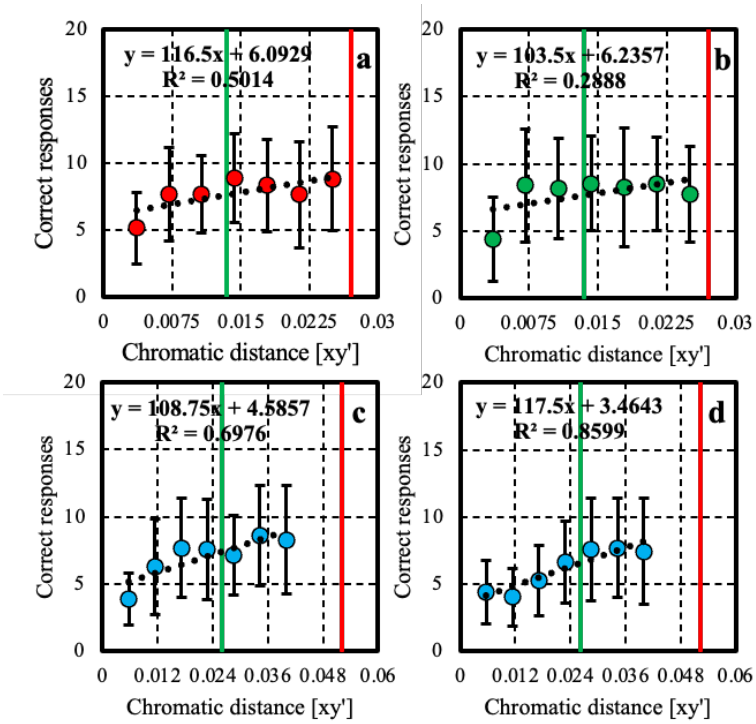

Fig. 4. The plots illustrate the objectively measured number of correct responses as a function of stimulus saturation, quantified by the xy′ chromatic distance in CIExy colour space. Panels (a) and (b) present results for the protan and deutan colour axes, respectively, using a stimulus size of 1 degree. Panels (c) and (d) show results for the tritan axis, measured with stimulus sizes of 1 degree and 0.5 degrees, respectively. The green and red vertical lines indicate the statistically averaged chromatic threshold and twice that threshold, respectively – values that are rarely exceeded in individuals with normal colour vision.

7. DISCUSSION

The current study introduces a novel, objective approach to colour vision assessment through eye movement analysis. The authors have designed a computerised colour vision test that incorporates dynamic luminance noise to obscure moving chromatic stimuli [16]. During experimental sessions, participants were instructed to identify the direction of chromatic moving stimulus. Unlike traditional colour vision assessments, which require individuals to respond by pressing a keyboard button after stimulus presentation, this study recorded eye gaze coordinates alongside subjective responses during the stimulus demonstrations.

The sensory thresholds of perceiving chromatic stimuli were determined using the method of constant stimuli. The chromatic threshold was calculated as a 62.5 % detection probability based on the psychometric function. In the case of protan,

deutan and tritan stimuli (size 1 degree), the 62.5 % detection probability based on the subjective responses of the participants was reached in almost all presented chromatic distances, indicating that the threshold value was even lower than the lowest intensities presented to the participants. For this reason, the subjective threshold of perceiving chromatic stimuli was successfully detected only for tritan stimuli with the angular size of 0.5 degreesc, which was on average 0.0177±0.0068 xy'.

Within the objective method of determining sensory threshold of perceiving chromatic stimuli, smooth pursuit eye movements were detected when participants successfully followed the moving stimulus, therefore providing an objective confirmation of their positive response. By combining and utilising various algorithms of saccade, smooth-pursuit and fixation detection developed by Larsson et al. [1], [15], and Nyström et al. [2], a function was created to automatically analyse eye movement data, identifying gaze positions associated with smooth pursuit eye movements, and therefore determining that eye movement direction corresponded to the actual motion of the object. The results clearly indicate that as the saturation of the chromatic stimuli increases, the likelihood of detecting smooth pursuit movements in the same direction as the object's motion also rises. However, in most cases, fitting the psychometric function, based on the number of "correct answers" or the number of stimulus demonstration sessions in which smooth pursuit was mainly detected in the stimulus direction, is not possible, since the individual performance necessary for fitting the psychometric function does not demonstrate a progressive manner. Furthermore, in some cases, when the stimulus level was high above the threshold level, no smooth pursuit was detected since the participants could give the correct answer without following the object.

Few studies have compared chromatic sensitivity threshold values across different retinal eccentricities [20], [21]. However, existing research suggests a general trend: chromatic resolution declines from the centre to the periphery, with a more pronounced increase in threshold values observed for the red-green opponent channel. Wu et al. (2024) found a significant reduction in chromatic sensitivity even in the near periphery. In that study, the saturation of chromatic stimuli was approximately twice the threshold value of the statistically average individual, suggesting that the direction of chromatic stimulus movement was, in most cases, detectable without direct fixation on chromatic stimuli [22].

Several studies have proposed that colour and luminance channels share a common motion detection pathway [23], [24]. Furthermore, Taore et al. (2022) demonstrated that smooth pursuit and optokinetic response could be successfully applied in classifying colour vision deficiencies and even estimating the severity of colour vision deficiency [14]. To our knowledge, no other studies have demonstrated that eye movement analysis can be applied to determine the severity of colour vision deficiency. The difference in the results obtained in the current study probably lies in the methodology applied for colour vision evaluation, as well as eye movement analysis. Contrary to the research by Taore et al. (2022), which applied a large grating that could induce the response of optokinetic nystagmus (OKN), the current study applied relatively smaller stimuli and explored smooth pursuit eye movements, which demonstrated to be of a voluntary basis [25]. Furthermore, the algorithms applied for smooth pursuit extraction from the raw eye movement data file were unambiguous – in many of the cases,

manual inspection of the data indicated a smooth pursuit response, while the algorithms were not capable of detecting these periods of following the moving object. Once again, this indicates that from both the perspective of the demonstrated stimulus and the algorithms available for smooth pursuit detection, smooth pursuit stimuli are not effective in detecting the severity of colour vision deficiencies.

By applying stimuli eliciting optokinetic response, eye movement analysis has been demonstrated to be a successful method in detecting the contrast sensitivity [26], visual acuity [27], [28], and, as previously mentioned, colour vision assessment [14]. Furthermore, other eye movement parameters have also been demonstrated to be effective in evaluating different visual functions, e.g., reflexive saccades in objective measurement of contrast sensitivity [29], microsaccade analysis in detecting stereopsis thresholds [29] and contrast sensitivity [31], as well as analysing dynamic visual acuity based on saccadic eye movement latency [32]. Therefore, further research on eye tracking applications in colour vision assessment should also explore other eye movement parameters, which have previously been linked to different visual functions, e.g., optokinetic response in dynamic visual stimuli and microsaccade parameters in static stimuli of colour vision.

8. CONCLUSIONS

This study has presented a novel, objective methodology for assessing colour vision through eye movement analysis, marking a significant advancement over traditional subjective techniques. The analysis of smooth pursuit movements highlights the potential for objectively evaluating chromatic sensitivity; however, the current approach is limited by the requirement of direct fixation on stimuli to accurately determine their motion direction. These findings emphasise the need for refining the experimental design to enhance its effectiveness. It is proposed that stimuli capable of eliciting optokinetic nystagmus and microsaccades may enable a more precise and objective evaluation of visual function. Expanding the applications of eye-tracking technology holds great promise for developing more comprehensive and reliable diagnostic tools in the field of vision science.

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