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Basic and Applied Studies of Human Visual Function: Implications for Visually Demanding Occupations

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BASIC AND APPLIED STUDIES OF HUMAN VISUAL FUNCTION: IMPLICATIONS FOR VISUALLY DEMANDING OCCUPATIONS

by

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DEDICATION

I dedicate this dissertation to my husband, Jesse. You have an unwavering belief in my abilities and took care of us and our family during these last three years. I could not have done this without you. You are truly an amazing husband and best friend. I am blessed to be your wife.

BASIC AND APPLIED STUDIES OF HUMAN VISUAL FUNCTION: IMPLICATIONS FOR VISUALLY DEMANDING OCCUPATIONS

JULIE A. LOVELL, PHD

UNIVBERSITY OF THE INCARNATE WORD

Color vision is a complex process providing important information about objects within our environment. Color vision deficiency either congenital or acquired can impact real world performance. Current working environments either require normal color vision or utilize color as a tool to highlight critical information. The use of color in the workplace provides several advantages. Hence, color vision screening is required for entry into professions and occupational certifications. Acquired color vision deficiency may also impact job performance requiring clinical screening. The present dissertation focused on the considerations outlined by the Commission on Behavior and Social Sciences when choosing a clinical test for occupational purposes. In order to address these considerations, I conducted a series of four studies.

The first study compared and contrasted three different computerized color vision tests for contrast sensitivity and analyzed how the minimum cutoff score differed between the tests. The results indicated that while log CS values were similar, there were enough differences between the values that caution should be applied when using the tests interchangeably for occupational screening. The second study assessed the Color Vision Field Test and found that it has excellent sensitivity and specificity for occupational screening when appropriate protocols are followed. The third study determined if the Cone Contrast Test could predict performance on the FM-100 Hue thereby providing a potential alternative test to the FM-100. Results indicated

the CCT may be an effective substitute for the FM-100 to provide certification of jewelry appraisers, but the small sample size warrants additional comparative validation to support sole utilization of the CCT. This study also revealed exceptional hue discrimination in jewelry appraisers, a possible effect of perceptual learning. The last study expanded previous research on cell phone distraction to auditory distraction with a navigational system. Delayed response time was found which poses a threat to safety.

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Introduction

Color vision is a complex process providing important information about objects within our environment.[1] Normal human color vision is based on three cone types that have spectral sensitivities ranging across the visible spectrum (Figure 1).[2] The visible spectrum, which ranges from 400 – 700 nanometers (nm), represents just a small portion of the electromagnetic spectrum. The three cone types, usually classified as long wavelength sensitivity (L), medium wavelength sensitivity (M), and short wavelength sensitivity (S), allow humans to see across the visible spectrum. [2]

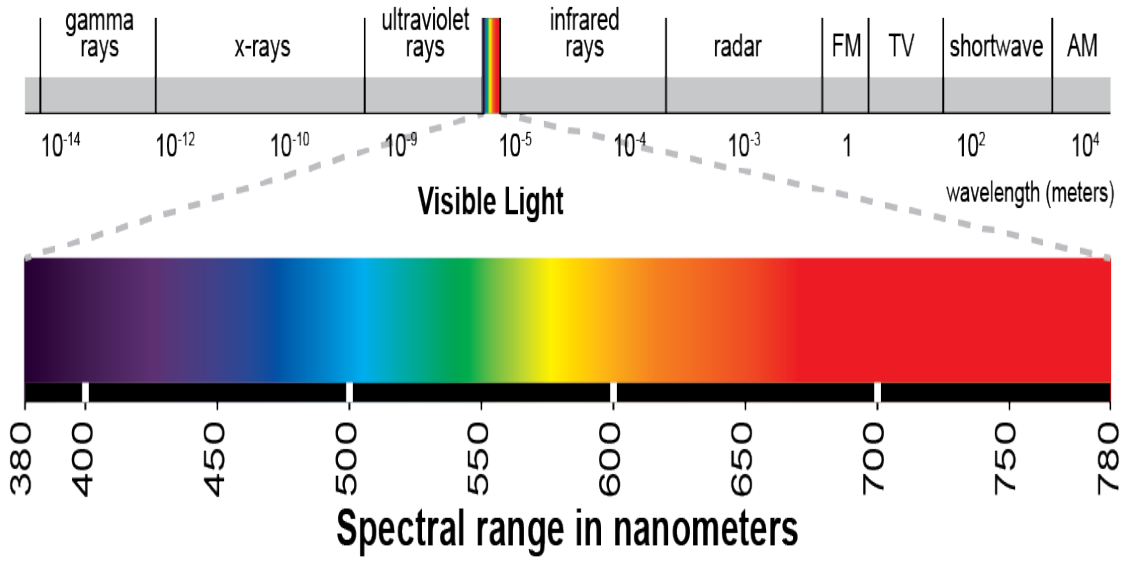

Figure 1. The visible light spectrum.[3] Humans can see only a small portion of wavelengths.

Figure 2 shows the spectral sensitivity peaks of the three cone types. The peak sensitivities are 570, 543, and 442 nm respectively though these values do shift depending upon how they are measured[4] and whether pre-retinal absorption by the macular pigment and crystalline lens are considered.[5] The normal functioning of trichromatic vision provides humans with the ability to see millions of colors and discriminate between wavelengths that are separated by less than a nanometer at 495 and 590 nm when the cone functions change most rapidly relative to one another.[6]

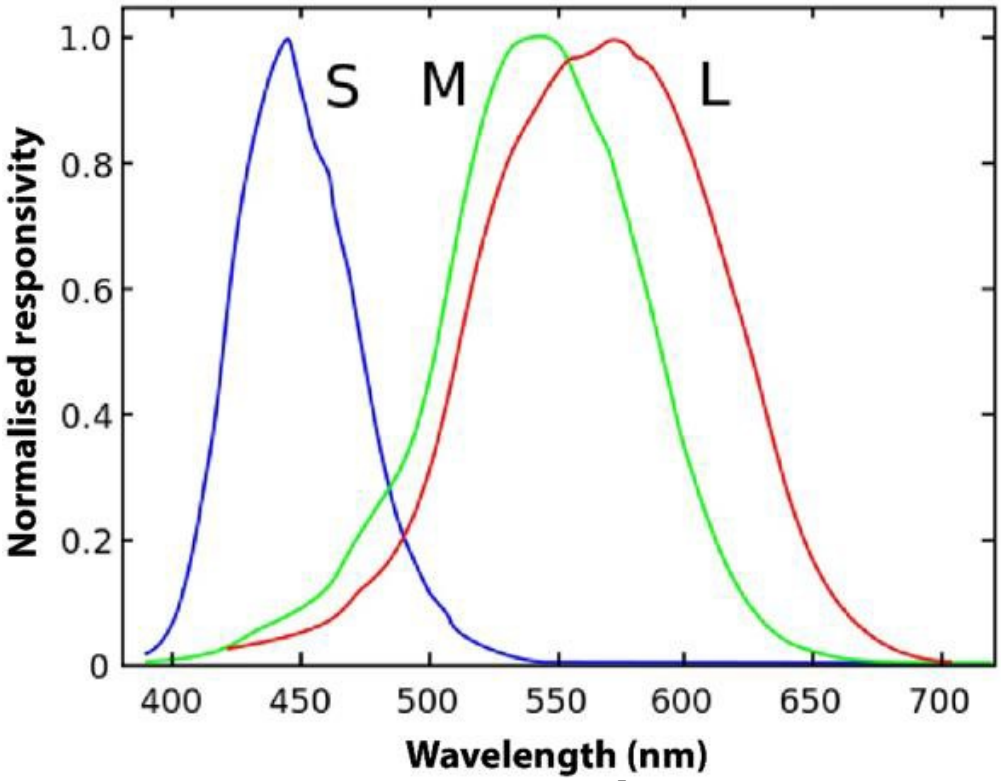

Figure 2. Absorption spectra of photoreceptors.[7] The peak sensitivities are approximately 442 nm (S), 543 nm (M), and 570 nm (L).

Abnormal color vision can impact color discrimination, identification and response time in various settings[1,8] and in the early age school environment as well.[9] Furthermore, color vision deficiency acquired from ocular systemic and/or neurological disease can impact real world performance.[10] Congenital color vision deficiency affects 8% of the male population and 0.5% of the female population.[11] Table 1 provides a summary of congenital color vision deficiencies by the three main categories and what cone photoreceptor is affected.[12]

Anomalous trichromacy occurs when the spectral sensitivity of the cone photopigment shifts. For a protanomalous trichromat, the spectral sensitivity of the L cone shifts toward the M cone as is shown in Figure 3. The M cone of a deuteranomalous trichromat shifts toward the L cone as shown in Figure 4.

Table 1. Congenital Vision Deficiencies.

Deficiency Type	Cones Affected	Description
1. Anomalous Trichromacy		
Protanomaly	L cone peak shifted to lower wavelength	Anomalous Trichromacy occurs when there is a shift in the spectral sensitivity of the cone.
Deuteranomaly	M cone peak shifted to higher wavelength	
Tritanomaly	S cone shifted but existence of tritanomaly debated[2]	
2. Dichromacy		
Protanopia	L cone is missing	Dichromacy occurs when one of the cone photopigments is absent.
Deuteranopia	M cone is missing	
Tritanopia	S cone	
3. Monochromacy		
Absence of L, M, and S cones	Congenital and hereditary lack of cones; patient only has rods	Monochromacy occurs when patient is born with only rod receptors (termed rod monochromacy or achromatopsia)
Rod		

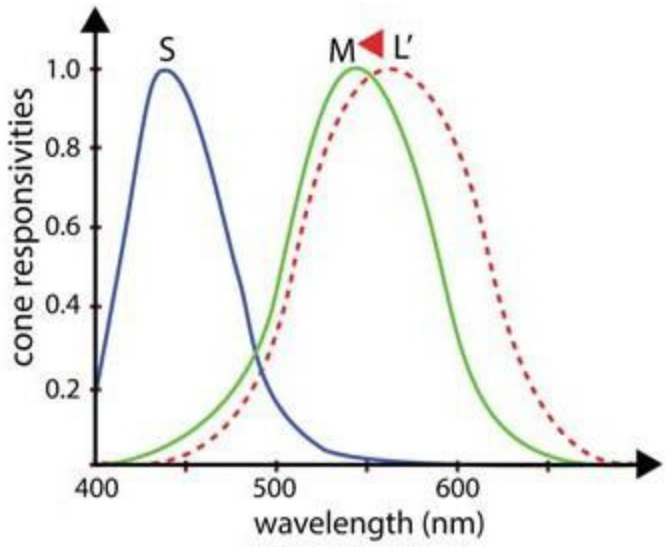

Figure 3. Protanomalous wavelength shift from long to medium wavelengths. Figure adapted from Petrovic and Fujita.[13]

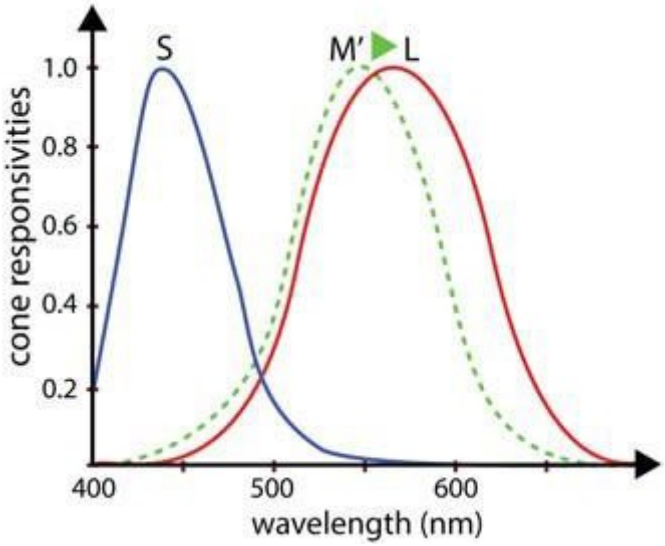

Figure 4. Deuteranomalous wavelength shift from medium to long wavelengths. Figure adapted from Petrovic and Fujita.[13]

For dichromatic deficiency, one of the three cone photopigments is missing. For example, a protanope is missing the L cone and therefore shades of red appear grey (Figure 5).The same can be said for a deuteranope when M cone is missing and greens appear grey (Figure 6).

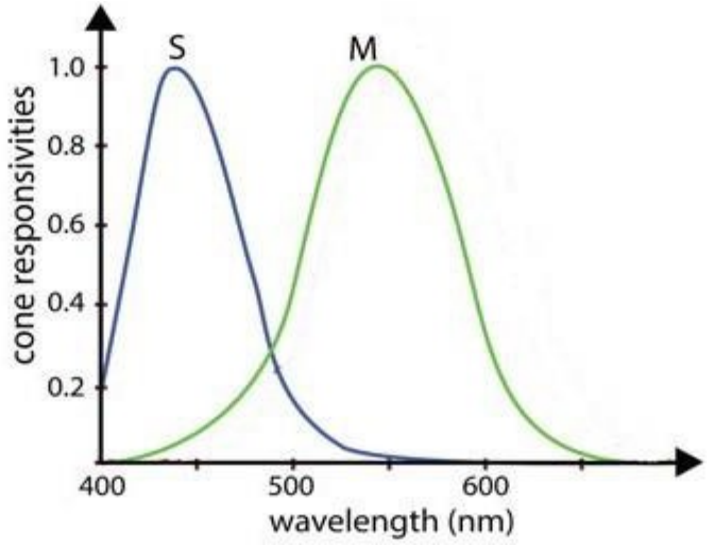

Figure 5. Protan dichromat spectral sensitivity. Figure adapted from Petrovic and Fujita.[13]

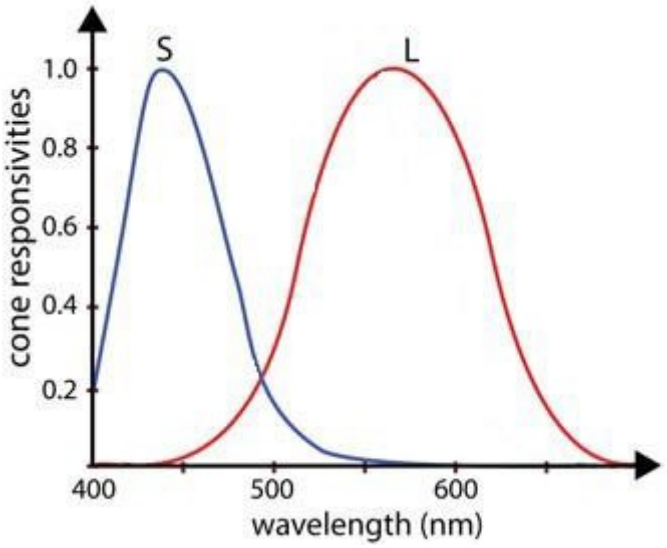

Figure 6. Deutan dichromat spectral sensitivity. Figure adapted from Petrovic and Fujita.[13]

With tritanomaly, the S cones spectral sensitivity shifts towards the M cone as shown in Figure 7 though the existence of hereditary tritanomalous vision has been questioned.[2] For tritanopia, the S cone is missing and blues appear green and yellows may appear white to red in color (Figure 8).

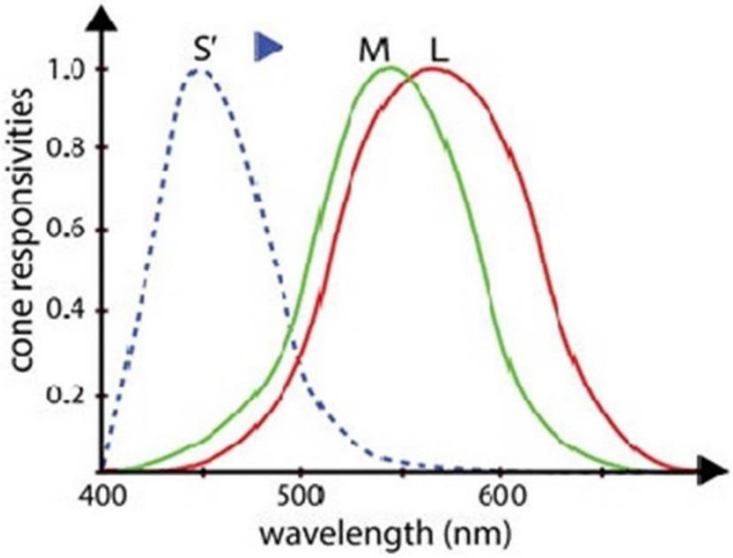

Figure 7. Tritanomalous spectral shift showing short wavelength cone moving towards long wavelength cone. Figure adapted from Petrovic and Fujita.[13]

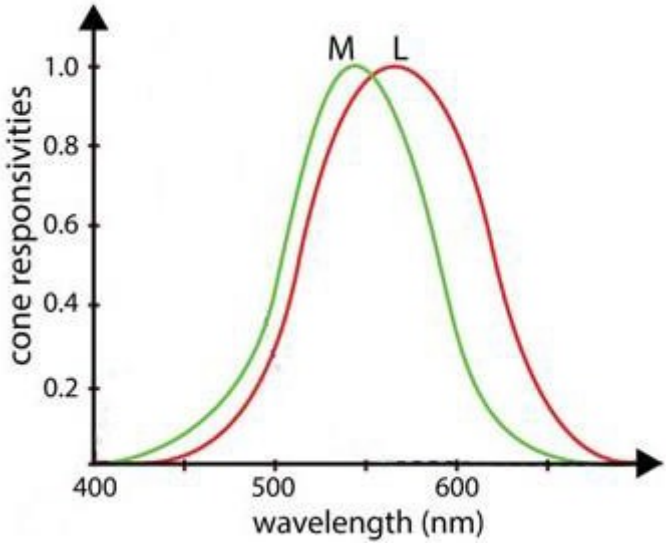

Figure 8. Tritan dichromat spectral sensitivity. Figure adapted from Petrovic and Fujita.[13]

Acquired color vision deficiencies affecting L, M, and S cones can occur through various types of disease: ocular, neurological, or systemic.[11,12] Occupational research has focused on red-green deficiencies. According to Dain, individuals with a protan-type deficiency pose a greater risk due to their lack of sensitivity to red wavelengths.[14] Koefoed et al. pointed out that past research in this area has significant design limitations.[15] Furthermore, research has not reflected the advancements in technology both from an occupational environment standpoint but in color vision tests which are now mainly computerized.[14,16,17]

The increased use of color in the workplace provides several advantages. Color makes objects easer to see.[18] For example, air traffic management systems use salient color display information to an air traffic controller (Figure 9).

Color allows objects to standout or pop out which is extremely useful when viewing crowded and complex scenes.[20,21] Figures 10 and 11 show how color can be used to identify information in a crowded grouping.

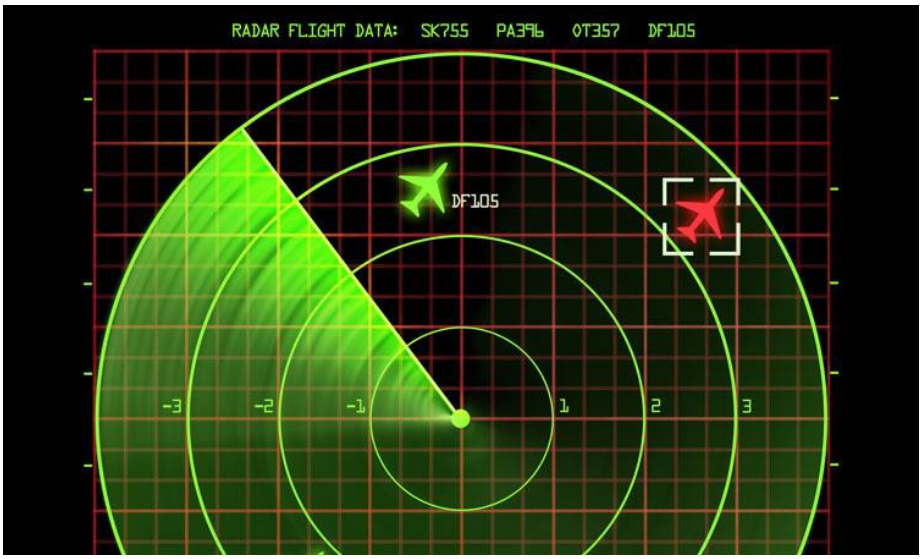

Figure 9. Air traffic management display.[19] Critical information that is displayed in color is easier to see than the objects and text displayed achromatically.

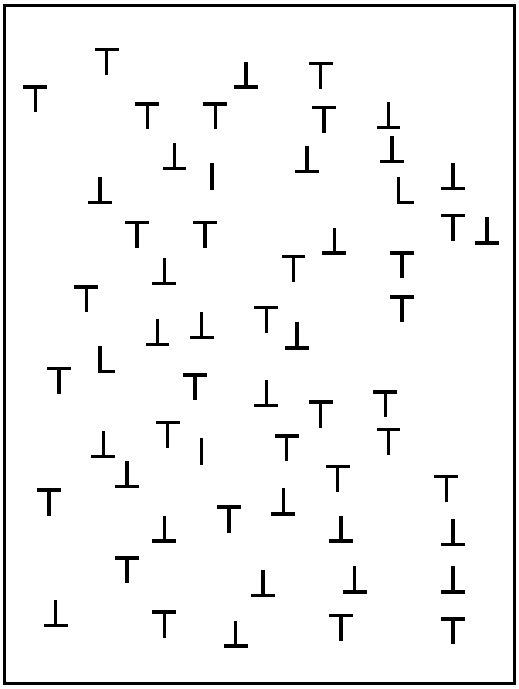

Figure 10. Crowded grouping of the letters I, L and T.[22] Achromatic letters are difficult to distinguish between in a crowded grouping.

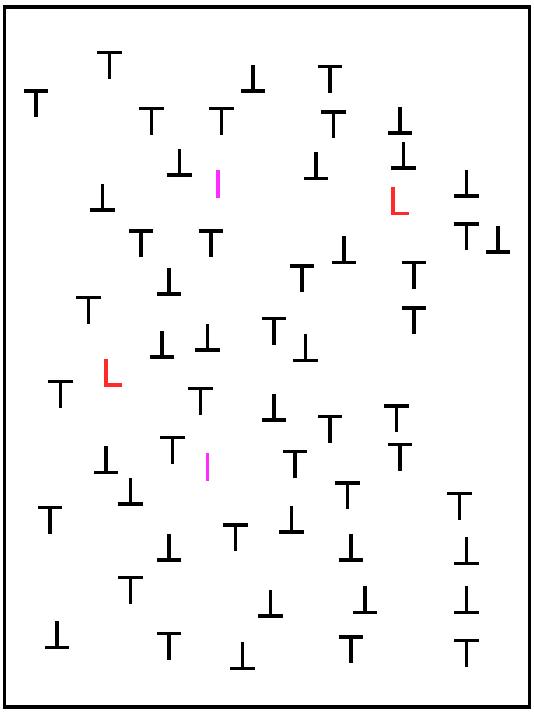

Figure 11. Crowded grouping of the letters I, L and T with color.[22] The letters that are in red and magenta are easier to identify than the achromatic letters in Figure 10, they "pop out."

Color can also be utilized as a way to group objects together or identify them as being similiar.[23] A classic example is that of a map where roadways are labeled in a red color, water is labeled in blue, and information/rest stops are shown in black (Figure 12). When compared to a black and white map (Figure 13), the map with color is easier to read and items of interest are easier to identify.

As demonstrated, when objects/text are linked to colors, they are easier to remember especially if they are relaying important information.[26] For instance, weather maps from the 1970s were black and white. While able to relay critical information about storms, the ability to identify the most severe weather is difficult (Figure 14). Advanced technology allows for the utilization of color to indicate severity or urgency of information (Figure 15).

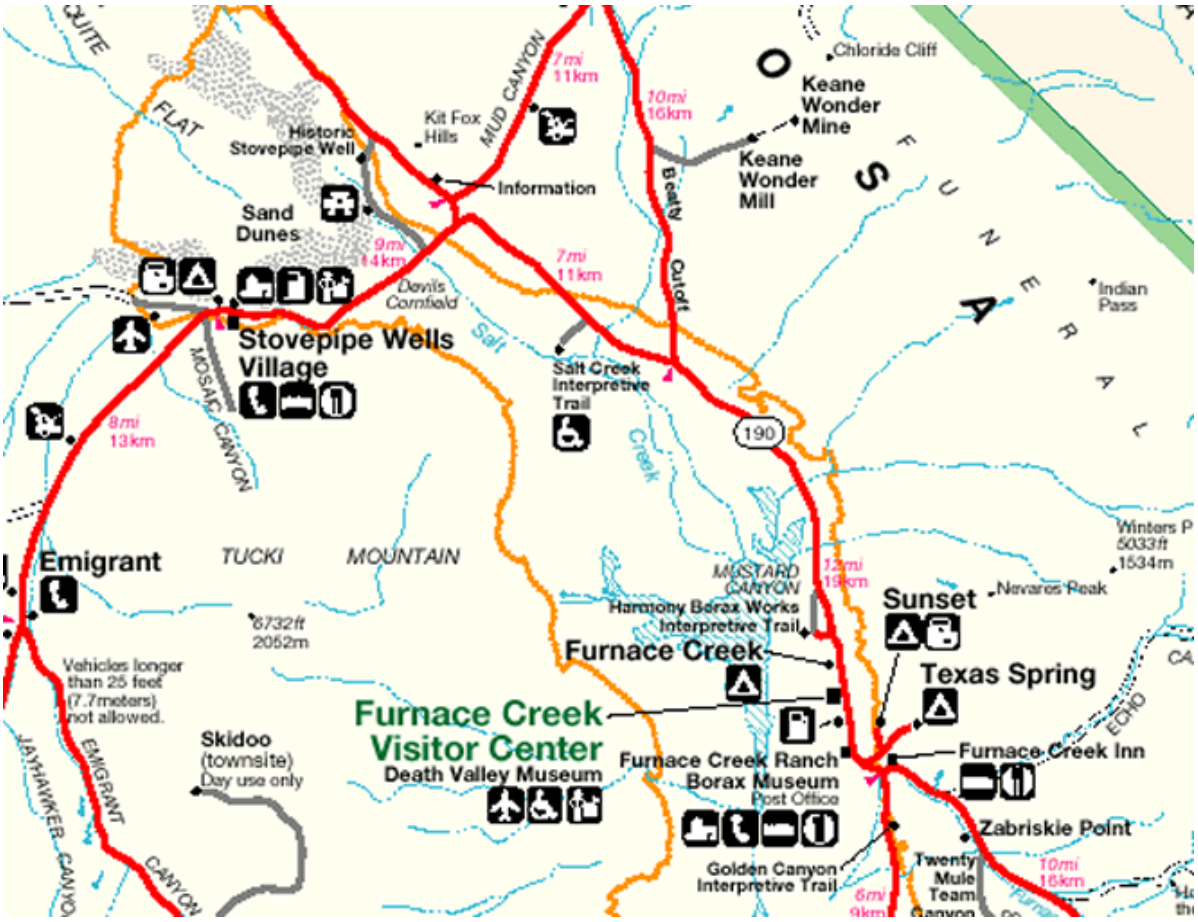

Figure 12. Color coded map.[24] The color of items of interest such as trails, roads, water,and boundaries make them easier to identify.

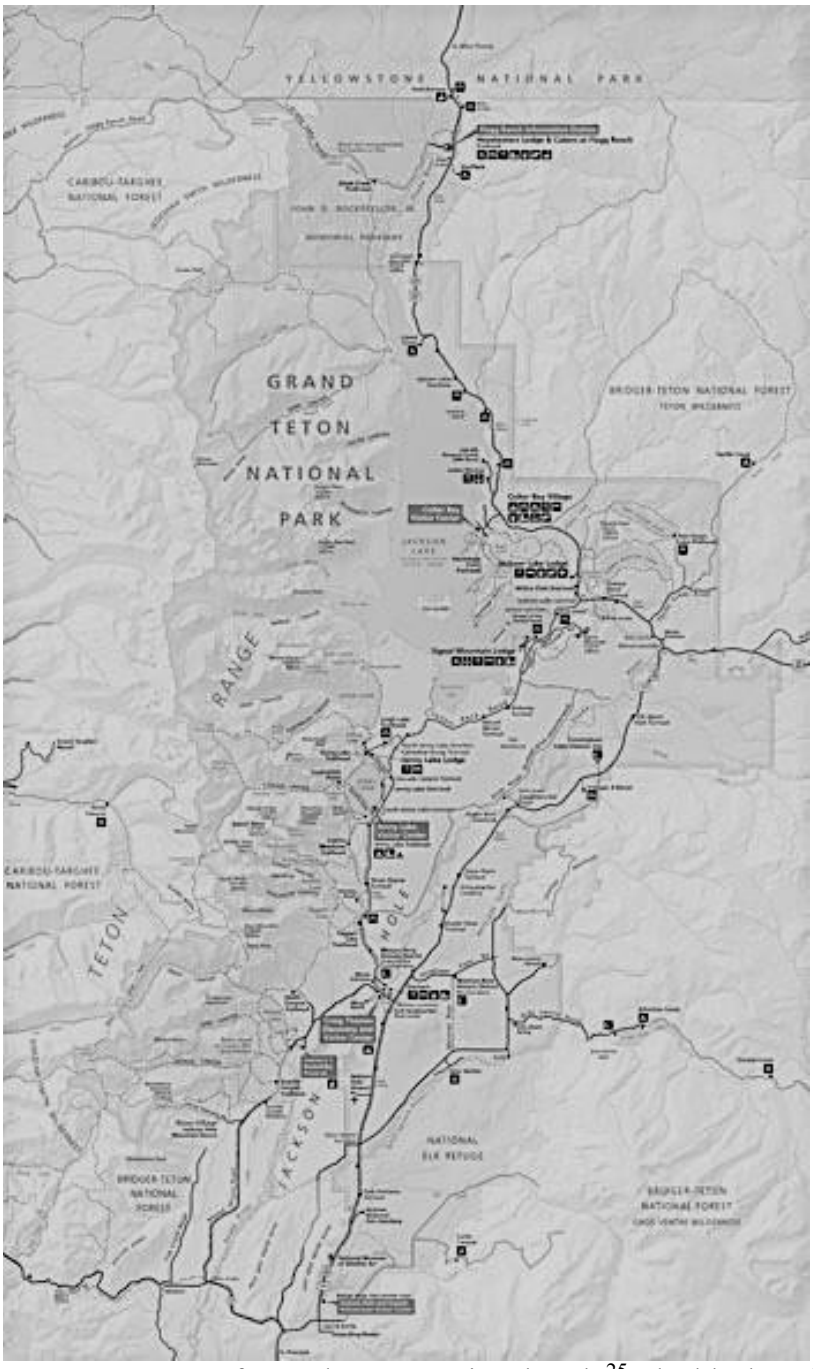

Figure 13. Map of Grand Teton National Park.[25] The black and white map makes it difficult to identify roadways, water and points of interest.

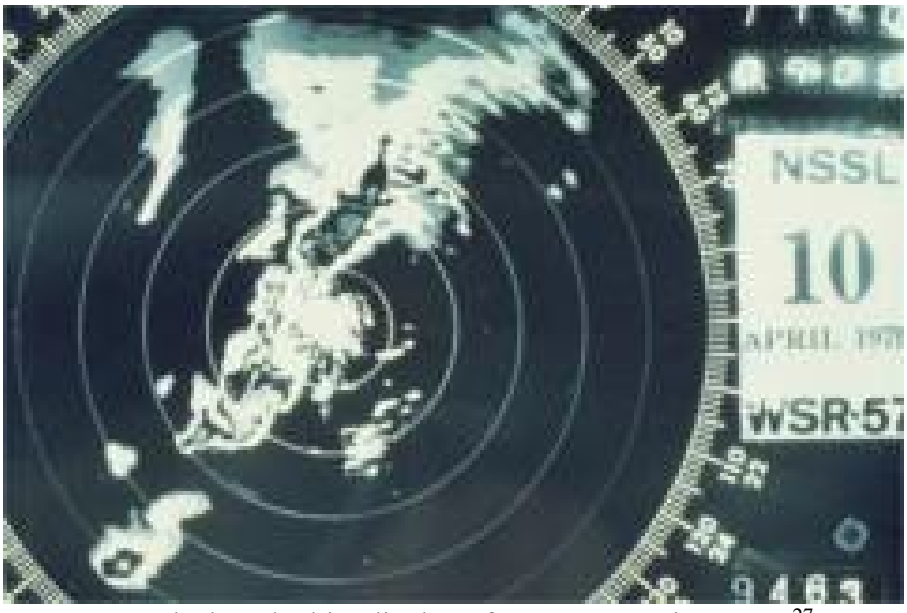

Figure 14. Black and white display of severe storm inn 1979.[27] Compared to Figure 15, it is difficult to identify the location of the most severe weather.

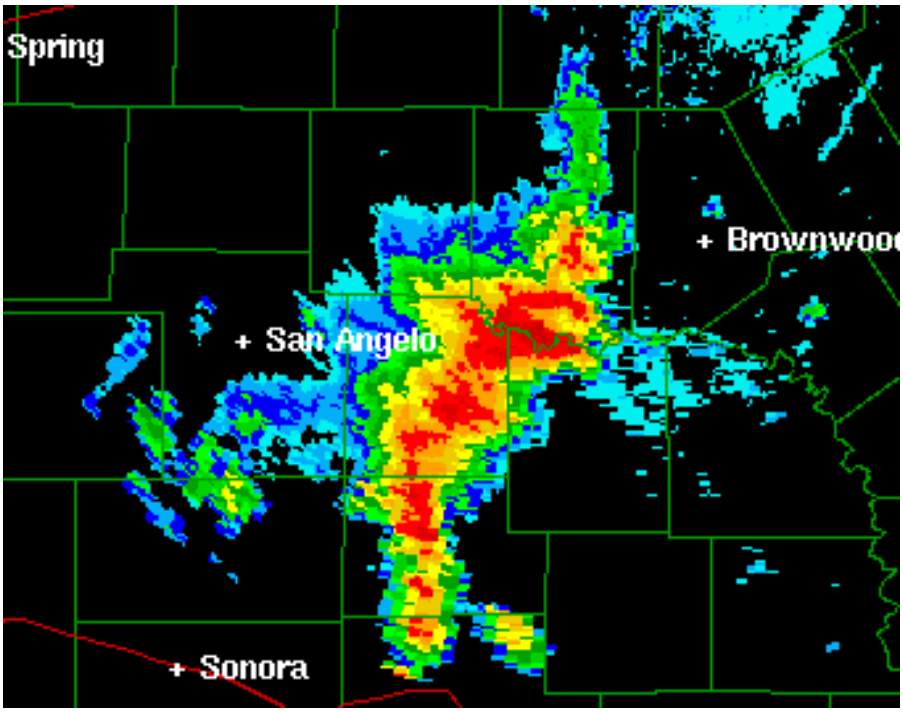

Figure 15. Weather map display in prototype cockpit.[28] The display is similar to weather radar screens that show severity or type of weather by color. Red is used to indicate the most severe weather.

When color is utilized in the work setting, it relays important information to the employee. Certain occupations require normal color vision to perform tasks safely. When an employee does not have normal color vision, the chances for accidents increase, like the FEDEX plane crash (Figure 16), leading to loss of life and millions of dollars' worth in damage.

Figure 16. Federal Express – Boeing – B727-232F (N-497FE) flight FX1478.[29] The crash left several crew members injured and destroyed the aircraft. The National Transportation and Safety Board determined the pilot was not able to recognize the precision approach path indicator (PAPI) lights due to his color vision deficiency, which may have been exacerbated by stress and fatigue.

Employers may require normal color vision for safety critical jobs such as in the transportation industry. Medical professionals, firefighters, police officers, or many armed forces career fields may not require normal color vision though degraded color vision can make daily tasks difficult.[30,31] In order to ensure employees have the appropriate color vision, color vision screening may be required before entering the career field while self-initiated vision screenings by the employee may pick up changes that could impact daily work and life performance.[32] There are several types of different tests available for such purposes.

Color vision tests can be classified into four categories: pseudoisochromatic plate tests

(PIP), arrangement tests, matching tests, naming tests.[14] PIP tests are based on an object or optotype that is a different color than the background. The colors utilized usually lie on what is known as the color confusion lines for protans (Figure 17), deutans (Figure 18), and tritans (Figures 19); lines of hues confused by the respective color vision deficient (CVD).

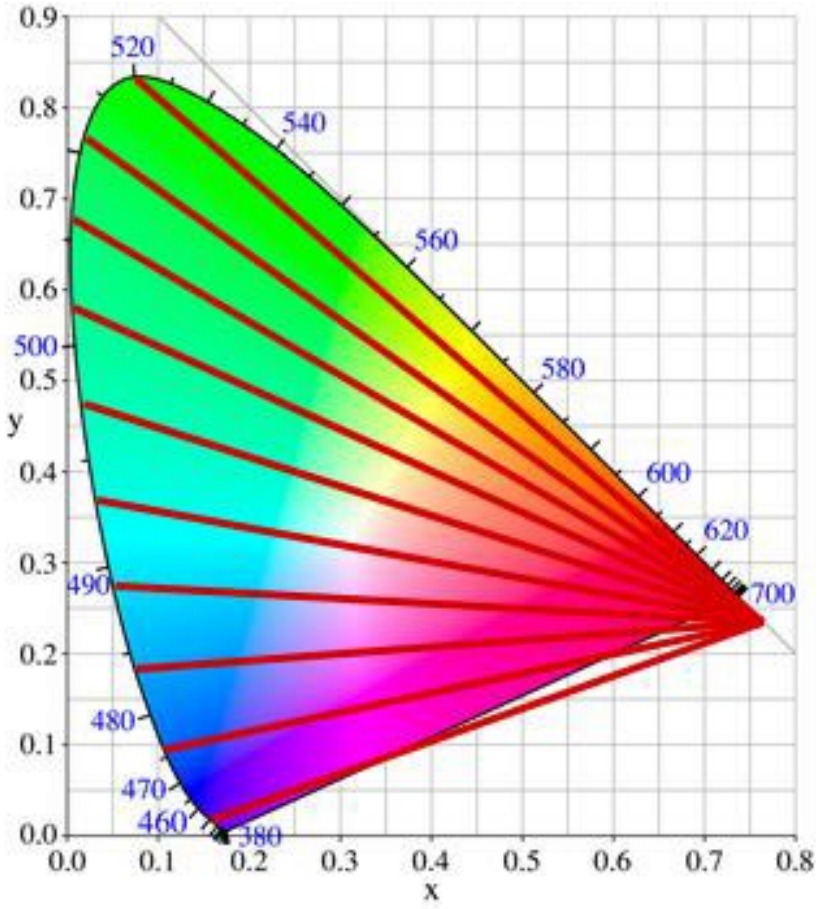

Figure 17. Protan (L cone) color confusion lines.[33] An individual with a protan deficiency will confuse hues along the lines in red in the figure.

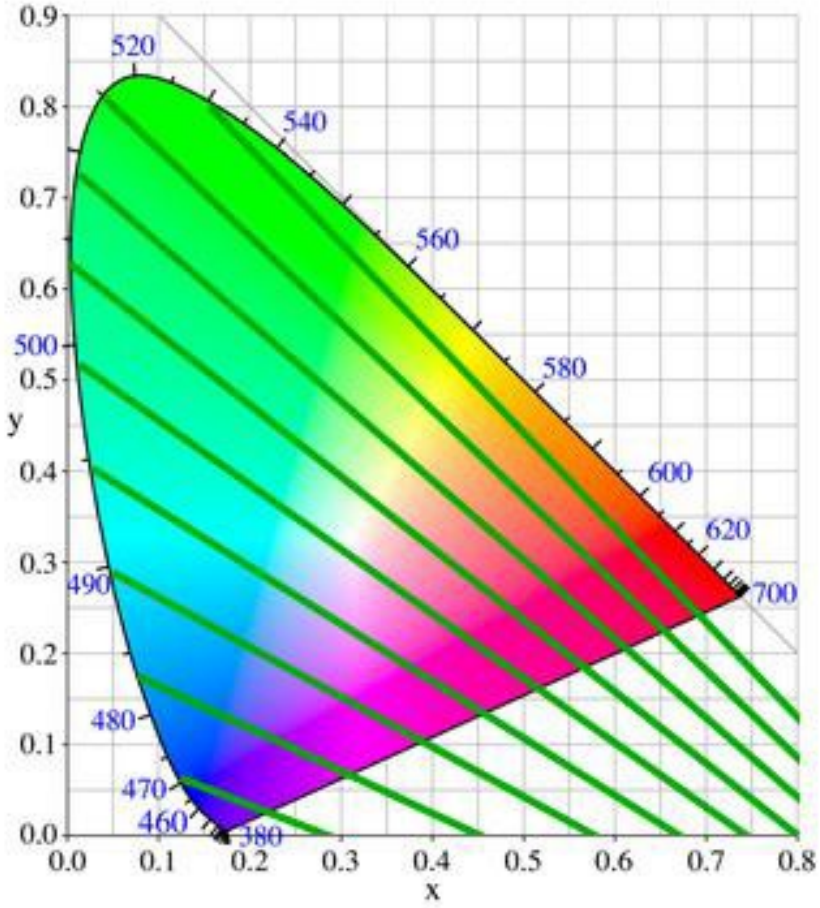

Figure 18. Deutan (M cone) color confusion lines.[33] An individual with a deutan deficiency will confuse hues along the lines in green in the figure.

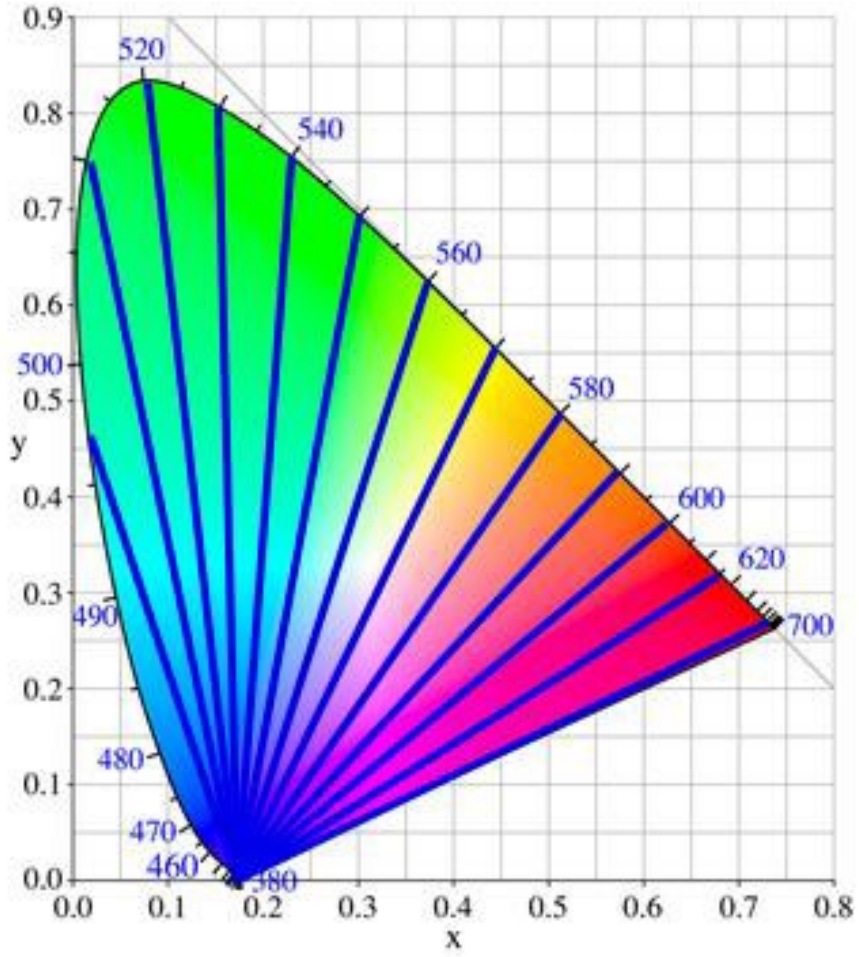

Figure 19. Tritan (S cone) color confusion lines.[33] An individual with a tritan deficiency will confuse hues along the lines in blue in the figure.

For example, the Ishihara PIP (Precision Vision, precision-vision.com, Figure 20), 24-Plate Edition is a pseudo-isochromatic plate test where the subject is asked to identify numbers seen by color vision normal (CVN) but not by CVD individuals. Included in the transformation plates are hidden digits in which a CVD can see a number or numbers while a CVN cannot. Ishihara's test is an excellent screening tool using vanishing plate (only CVNs see the numerals), transformation plates (seen as one or two numerals by CVNs but as different numerals by CVDs), and hidden plates (seen as numerals by CVDs but unseen by CVNs).[34,35]

Figure 20. Ishihara plate example. The plate shown here is visible to CVNs but not CVDs.

Arrangement tests require the subject to 'sort' or 'arrange' colors in logical order according to perceived color (hue).[14] There are several different types of arrangement tests such as the Farnsworth Munsell-100 Hue (FM-100). The FM-100 consists of 85 caps ranging in hue (Figure 21) and subjects with a CVD will make errors in the arrangement of the caps along the color confusion lines. Age has been shown to impact the performance on the FM-100.[36]

Color matching tests, such as the anomaloscope, are another option to utilize and they provide more definitive diagnosis of type and severity of color vision deficiency, with the Rayleigh anomaloscope considered a gold standard for red-green CVD.38 Different versions of the anomaloscope are available. As an example the Oculus anomaloscope (Oculus Inc., oculus.de/us/frontpage, Figure 22) is a color matching test for the diagnosis of red-green deficiency. The stimulus is a circular field with a red (670 nm) and green (545 nm) mixture on

Figure 21. FM-100 Hue.[37] There are 85 caps in the test with anchor caps at each end of the box. The subject is asked to arrange the caps by hue.

top and a yellow (589 nm) on bottom. The subject is asked to use a knob to adjust the red-green mixture on top to match the yellow on the bottom, or a forced choice algorithm is used in which the patient depresses separate buttons for same color and brightness versus different, iteratively identifying the matching point and range over which matches occur. If a subject has an M cone deficiency, they will require more green on the top field to obtain a match to the yellow. If a subject has an L cone deficiency, they will require more red on the top field to obtain a match to the yellow.

Figure 22. The HMC-Anomaloscope with laptop. The anomaloscope is considered the gold standard for diagnosing red-green color vision deficiency.

The last type of color vision tests are known as naming tests and they are utilized more frequently in occupational settings.[14] Lantern tests are a type of naming tests. They vary in aperture configuration and size, filters, and colors, but have been developed and utilized to assess employees' color vision occupational suitability.[39] The lantern tests are not meant to be diagnostic in nature but to assess an individual's ability to perform occupational tasks such as identifying the color of a railway signal. The original Farnsworth Lantern test (no longer in production) was based on the ability of seamen to correctly identify maritime signal lights. The Titmus Stereo OPTEC test has supplanted the Farnsworth Lantern and is still used for some occupations. Another example of a lantern test is the RailCorp Lantern (Figure 23). The subject is required to identify the color of light displayed from the lantern while sitting at a specified distance from the lantern.

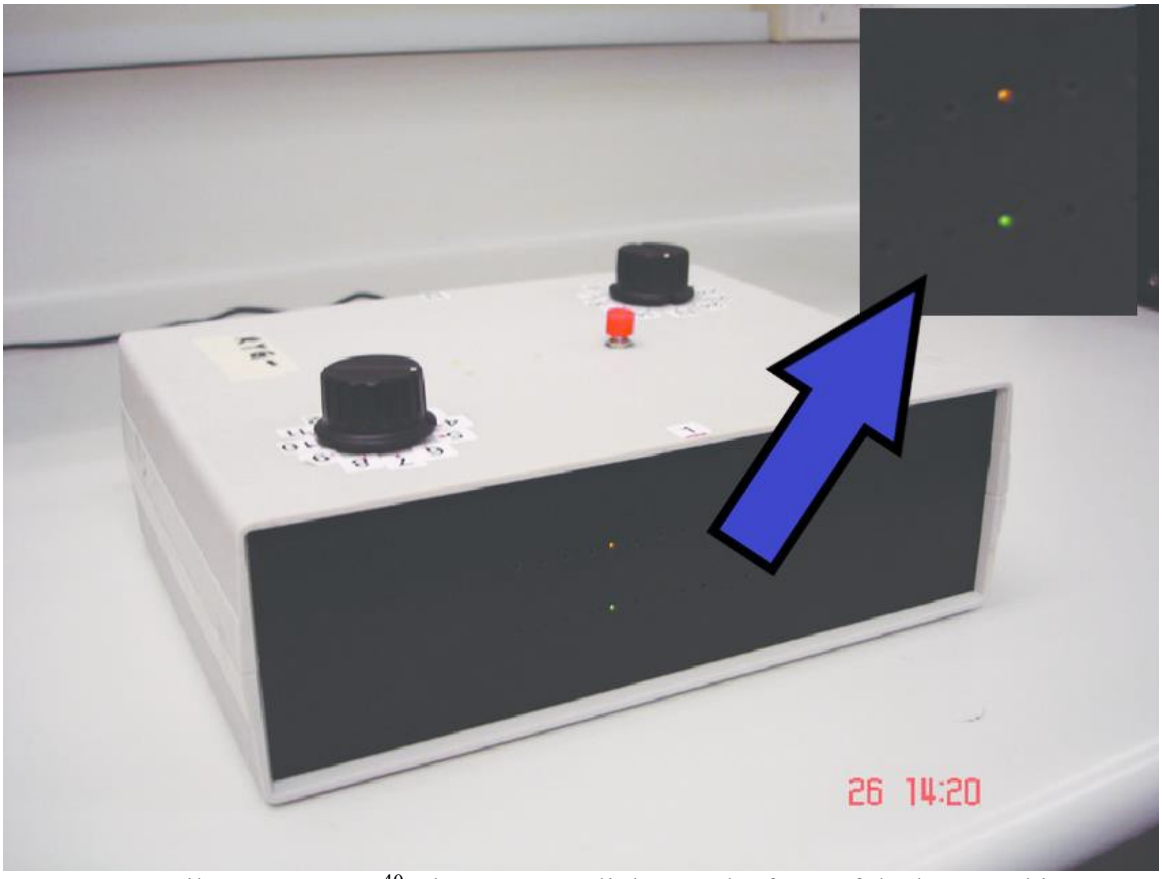

Figure 23. RailCorp Lantern.[40] There are two lights on the front of the box. Red is on top and green is on the bottom. Subject is asked to identify color of the light shown on the box.

The aforementioned tests can be and have been utilized for occupational purposes. When considering a clinical tests for occupational purposes, the Commission on Behavior and Social Sciences outlined four considerations.[41] First, while clinical tests can determine presence, type and/or severity of deficiency they are not set up to establish a minimum required score to determine job entry. Second, practical field tests may be more suitable since ideally it replicates tasks required on the job. Third, not all clinics will have the required tests and if they do, not all personnel will have the proficiency required to administer the test correctly. Last, clinical tests do not provide information on how the work environment and the distractions associated with said environment effects test results. In order to address these considerations, I conducted a series of four studies.

Synopsis of Experiments

Study 1

Computerized color contrast sensitivity (CS) tests that aim to determine type and severity of color vision deficiency (CVD) have been developed and are available but data on agreement between the tests is lacking. Furthermore, they are not designed to establish minimum required scores for job entry. This study assessed three computerized color contrast sensitivity tests to determine data agreement and then analyzed how a minimum cutoff score for entry into a military pilot career differs between the three tests.

Study 2

As previously mentioned, practical field tests may be more suitable than clinical color vision tests since they ideally replicate tasks required on the job. Historically, railways have tested color vision using a variety of methods from wool tests and color sticks to lantern tests.[39] The lantern tests simulate signal lights used on the railway.[42,43] The distances used in these tests, while accurately reflecting the angular sub-tense of the signal light size, cannot be couched as replication which according to the International Committee on Illumination (CIE) is an important part of developing a field test.[44] This study assessed a signal light test called the New Signal Light Test (NSLT). The signal light stimulus is an exact replica of what is utilized on the railway system in both stimulus size and wavelength color. Second, the test is performed at the exact distance a railway employee is expected to correctly identify the color of a wayside signal.

Study 3

The Farnsworth-Munsell 100 Hue (FM-100) test is often used for vocational purposes where hue discrimination is of the upmost importance, such as in the field of jewelry appraisals where small errors in hue discrimination can lead to significant differences in gemstone valuation. However, not all clinics will have the FM-100. The purpose of this study was to

determine if the cone contrast test (CCT, Innova Systems Inc.), a more rapid computer-based test which provides quantitative cone sensitivity scores, can predict performance on the FM-100 thereby providing a potential alternative test to the FM-100 for initial and periodic screening of jewelry appraisers as required by the NAJA. Superior hue discrimination was observed in jewelry appraisers compared to age-matched norms, and this finding was pursued rigorously in the context of neural plasticity and perceptual learning.

Study 4

The final study focuses on how distractions impact vision. Clinical tests are not designed to provide information on how the work environment impacts test results. Past research has noted that perception thresholds play a critical role in target detection, especially those that have low contrast, luminance and/or are displayed in the periphery outside the line of sight.[45] Others have reported that verbal communication increases task response time and contrast sensitivity for small, low-contrast letters.[45,46] The purpose of this study was to investigate the impact of a simulated navigational screen on response time and accuracy for detecting centrally displayed low luminance and chromatic contrast targets.

Study #1: Comparison of Three Computerized Color Vision Tests

Introduction

Computerized color contrast sensitivity (CS) tests that aim to determine presence, type and severity of color vision deficiency have been developed and are available[17,47,48] but data on agreement between tests is lacking. Color vision tests are essential for determining the presence, type, and severity of congenital or acquired color deficiency, or validation of normal color vision for occupational purposes. Current studies comparing color vision tests have focused on different types of color vision tasks [17,49] or single test versus multi-test protocols.[50,51] The tests utilized in

these studies have focused on the four groups of color vision tests: pseudoisochromatic plate tests, arrangement tests, matching tests (or naming) tests,[7] and computer-based tests focusing on color contrast.[14] The purpose of the present study was to determine data agreement between three computerized color vision tests.

The cone contrast sensitivity test was initially developed for and by the United States Army Aeromedical Research Lab.[52] Computer generated charts displayed letters visible to only L, M, and S cones (Figure 24). Isolation of the cone type is achieved through adaptation, a method comparable to silent substitution in which each stimulus is visible only to the pathway of interest.[53] For example, the L cone letters stimulate L cones in systematic fashion from high to low contrast. While due to the over-lapping cone functions, the M and S are also stimulated by the L cone letters. The amount of stimulation is essentially equal to the stimulation of the cones by the grey background. Hence, L cone letters stimulate M and S cones with zero or subthreshold levels of cone contrast. The same applies for each set of cones stimulated, "silencing" the non-targeted cone types. With this type of cone isolation technique, the luminance of the display is too bright to stimulate rods. The original CCT proved slightly sensitive to hereditary as well as acquired CVD.[52] The United States Air Force School of Aerospace Medicine enhanced the test to present randomized L, M, and S cone CS letters on a computer display.[47] In the original CRT based version, subjects provided a verbal response and scoring was achieved by marking the letters correct on a pre-printed score sheet. Contrast ranged from 27.5% to 1% for L and M cones and 173% to 7% for S cones in 0.16 logarithmic steps (two letter per step; 0.08 log contrast units per letter).

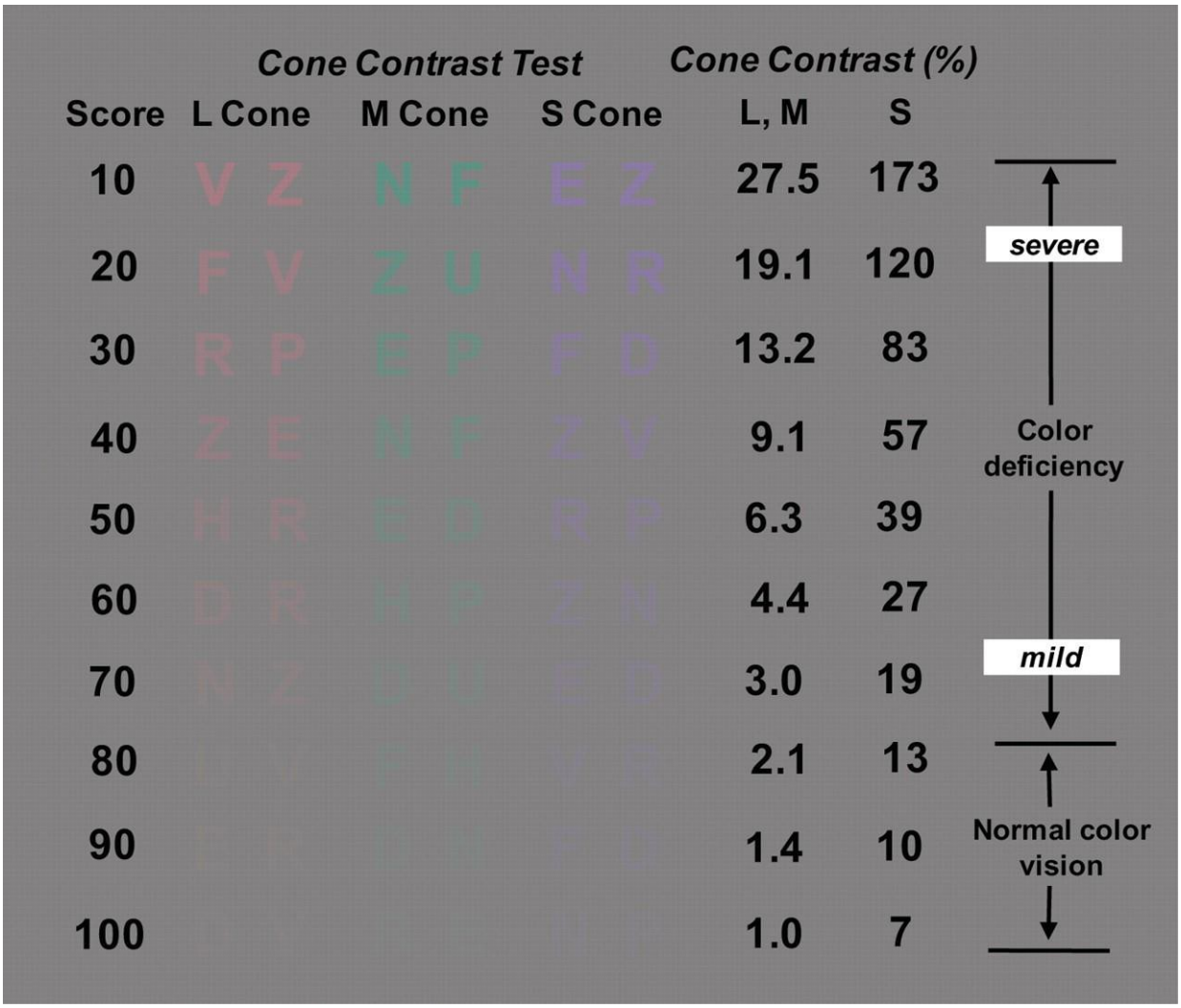

Figure 24. Original Computer Generated Cone Contrast Sensitivity Test contrast scale.[54]Letters decrease from a clearly visible cone contrast down to a threshold level (L and M cone: 27.5% to 1%; S cone 173% - 7%) in 0.16 logarithmic steps (two letters per step;
0.08 log contrast units per letter).

The Innova CCT (Innova Systems, innovasystemsusa.com) is a computer-based test developed under a cooperative research and development agreement (CRADA) between USAFSAM and Innova Systems, Inc. It presents letters visible only to L and M cones (20/330 letter size) and S cones (20/400) at progressively lower cone contrasts (Figure 25). A letter appears briefly (5 seconds) in the center of the display and the subject uses a mouse to select the letter seen from the adjacent matching display. An adaptive staircase program determines the

lowest detectable L, M, and S cone contrasts seen as well as average response times. Response time is defined as the time between letter presentation and subject response, averaged across all responses. The Innova CCT has proved comparable to the anomaloscope for detection of type and severity of hereditary CVD as well as acquired CVD associated with ocular systemic and neurologic disease.[52,54] As noted earlier, the version used in this study was adjusted to slightly lower cone contrasts (0.8% to 16% for L and S cones and 8% to 128%) on a Microsoft Surface Display to enable threshold Innova CCT measures comparable to the original CRT-based system.

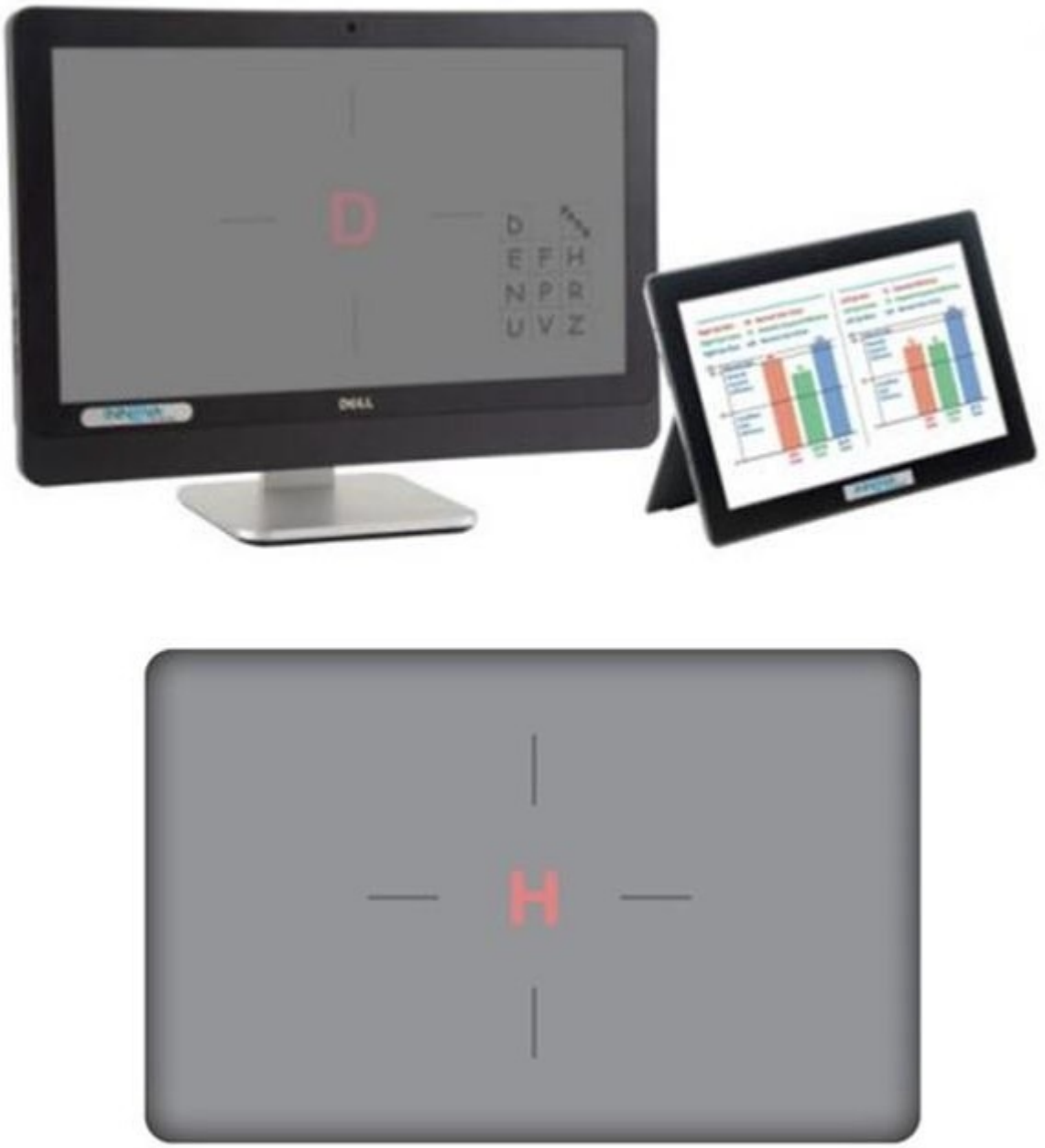

Figure 25. The Innova CCT in the present study can be displayed on a calibrated Microsoft Surface or a large screen monitor and testing can be conducted at a standardnear distance (3 feet) or at distance as well.

Like the original Innova CCT, the Konan Cone Contrast Test High-Definition (Konan CCT-HD®, Konan Medical, konanmedical.com) selectively stimulates L, M, and S wavelength cones at progressively lower contrasts to determine the lowest cone contrast visible (i.e., determines cone contrast sensitivity, CS) for the diagnosis of hereditary and acquired color vision deficiency

(Figure 26). It utilizes a well-established, response-driven, staircase method (psi) to determine not only CS but added parameters such as the slope of the function between stimuli and responses in addition to impact of factors not directly related to threshold.[55] Recently, the test has been successfully utilized to track minute changes in color vision in a patient with ocular siderosis.[56] A Landolt-C optotype is presented in the middle of the screen in one of four orientations. The subject depresses a keypad to indicate the direction of the gap in the C. The threshold changes based on the response of the subject.

Figure 26. Konan CCT-HD®. The Konan CCT-HD® uses a 4-alternative forced choiceadaptive staircase method requiring the subject to 'detect' the location of the gap in the Landolt-C optotype.

The Nordstrom Consulting, Inc. Cone Contrast Test (NCI, ncivision.com) is a computer-based contrast sensitivity test that provides several optotype options for the clinician or researcher (i.e., 4-position Landolt-C, Tumbling E's, Letters, Numbers, etc., Figure 27). The NCI (Ver. 14) utilizes Landolt Rings in four positions visible only to L, M, and S wavelength cones in staircase fashion to determine cone CS thresholds. The test is administered in scotopic conditions after a 10-to-12-minute dark adaptation period. The stimulus is shown on an In-Plane-Switching screen with an automatic retest if thresholds are below a specific level.

Figure 27. NCI Vision Systems Display.[57] The NCI provides options to utilize different optotypes to include a 4-alternative forced choice with a Landolt-C or a 10-alternative forced-choice with cone contrast letters.

Walsh et al. investigated multiple types of color vision tests to determine their suitability for classifying military members for occupational demands.[17] They found good agreement among different tests and noted that computerized tests may have an advantage over traditional

PIP tests in that they eliminate the tendency of applicants to try to memorize PIP plates and sequences. Walsh et al. also noted that while tests designed to screen for congenital and hereditary color vision deficiency are clinically relevant, they do not address functional color vision. Gaska et al. did address functional vision (i.e., operationally relevant tasks) by investigating CVDs performance on operationally based tasks and their performance on the Innova CCT.[58] While they did find lower Innova CCT scores and reduced performance on operationally based tasks, the impact of this performance reduction was not clearly significant.

The purpose of the present study was to determine data agreement between three color vision tests all able to determine the presence, type and severity of CVD. The three tests are the Konan CCT-HD®, NCI, and a modified version of the Innova CCT using contrasts to achieve threshold levels comparable to those used in the original Innova CCT.[47,54,56] It is our intent to reveal any differences in validity (i.e., sensitivity and specificity), between tests. In the interest of offering useful data to the Department of Defense and related organizations using these tests for occupational purposes, we included an assessment of cut-off scores currently used in such settings. Further, we added suggestions and reveal possible strategies to improve sensitivity and/or specificity.

Methods

Subjects

We recruited fifty subjects (mean age 27 ± 9; 34 males and 16 females) from the local community who participated in the study. Subjects' color vision status was confirmed by the Ishihara PIP and the anomaloscope. All CVDs showed anomaloscope matching ranges and midpoints which agreed with values obtained with the three tests. Subjects were then divided into two groups, CVN (n = 25, mean age 24 ± 3; 10 males and 15 males) and CVD (n = 25, mean

age 30 ± 12; 24 males, 1 female). There were seven protan and 18 deutan CVDs. Each subject provided written informed consent in accord with our IRB-approved protocol.

Procedures and Materials

After subjects were classified as CVN or CVD by the Ishihara PIP and the anomaloscope, the Konan CCT-HD®, NCI, and Innova CCT were performed separately for right and left eyes according to manufacturer's instructions. Subjects performed the test with correction for best visual acuity for near viewing distance at 3 feet (91.4 cm), and if presbyopic near correction was provided. No subjects were allowed to wear tinted spectacle or tinted contact lenses. Test order was randomized across subjects, and computerized color vision tests were performed in a darkened room. All CVDs type of deficiency agreed with anomaloscope findings.

Statistical Analysis

Two-way repeated measures ANOVA across systems was run to determine if there was a significant difference between right and left eyes. No difference was found between eyes across tests. The higher of the two scores was used in the final analysis since we considered this each subject's best effort. Repeated measures ANOVA also was performed to determine if there were significant differences between the test results followed by post hoc paired t-tests corrected for multiple comparisons to determine where specific differences lie. Further analysis was conducted to determine if there were differences between tests for abnormal and normal cones.

Results

CVN Results

Two-way repeated measures ANOVA showed no difference between right and left eyes acrosstests for CVNs ($F = 0.05$, $P > .82$). There was a significant difference in CCT log CS scores between tests ($F = 2181.45$, $P < .001$). Post hoc comparisons with Bonferroni adjustments

for nine comparisons between the tests for L, M, and S cones are shown in Table 2. Figure 28 shows the mean log CS (± 2 SE) by tests across cone type.

Table 2. Post Hoc Comparison of Tests Between Cone Type.

Cone Type	Test	Mean	Mean Difference	95% CI	*P* Value
L	Konan CCT-HD®	2.09	0.21	.153 to0.264	< .001
	Innova CCT	1.88			
L	Konan CCT-HD®	2.09	0.24	.192 to0.289	< .001
	NCI	1.85			
L	Innova CCT	1.88	0.03	0.01 to 0.07	= .09
	NCI	1.85			
M	Konan CCT-HD®	2.05	0.13	.085 to0.175	< .001
	Innova CCT	1.92			
M	Konan CCT-HD®	2.05	0.21	.153 to0.262	< .001
	NCI	1.84			
M	Innova CCT	1.92	0.08	.040 to0.114	< .001
	NCI	1.84			
S	Konan CCT-HD®	0.99	-0.07	-0.16 to 0.02	= .14
	Innova CCT	1.05			
S	Konan CCT-HD®	0.99	0.17	.077 to0.259	< .001
	NCI	0.82			
S	Innova CCT	1.05	0.23	.219 to0.250	< .001
	NCI	0.92			

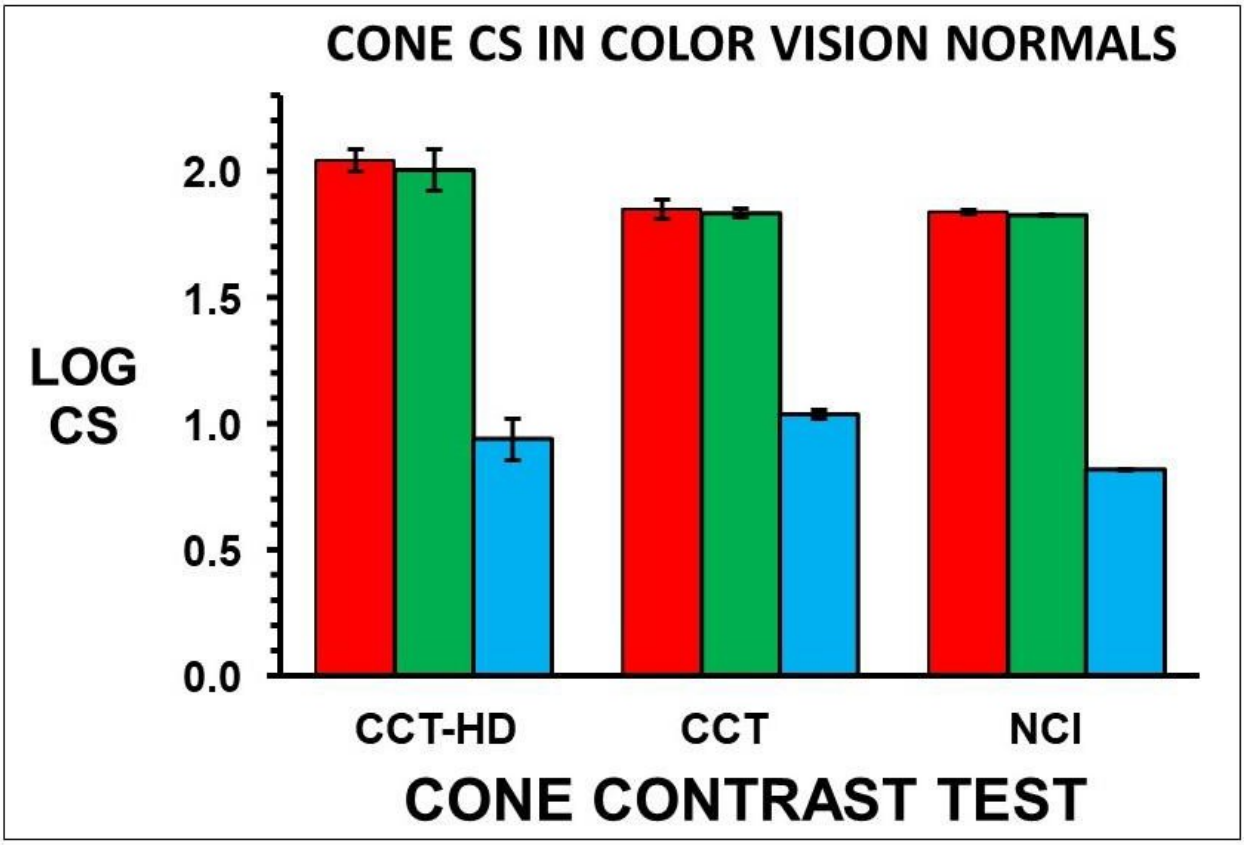

Figure 28. Mean Log CS (± 2 SE) by Cone Type. Konan CCT-HD® yields higher Log CS for L and M WS cones. NCI yields lowest threshold for S cone.

CVD Analysis

Two-way repeated measures ANOVA showed no difference between right and left eyes across tests for CVDs ($F = 1.09$, $P > .30$). Additional analysis combined the scores for the abnormal cones (L and M) regardless of CVD type, the normal cones for CVDs and S cones for CVDs. CVDs also showed a difference between systems ($F = 585$, $P < .001$). Post hoc comparisons with Bonferroni adjustments for nine comparisons between the tests for abnormal, normal and S cones are shown in Table 3. Figure 29 shows the mean log CS (± 2 SE) by abnormal, normal, and S cone for CVDs.

Table 3. Post Hoc Comparisons Between Tests for Abnormal, Normal, and S Cones.

Cone Type	Test	Mean	Mean Difference	95% CI	*P* Value
Abnormal	Konan CCT-HD®	1.18	0.3	0.22 to 0.38	< .001
	Innova CCT	0.88			
Abnormal	Konan CCT-HD®	1.18	0.08	.005 to0.164	= .04
	NCI	1.10			
Abnormal	Innova CCT	0.88	-0.22	-0.293 to -	< .001
	NCI	1.10		0.135	
Normal	Konan CCT-HD®	1.80	0.02	-0.04 to 0.08	= .46
	Innova CCT	1.77			
Normal	Konan CCT-HD®	1.80	0.06	-0.02 to 0.13	= .12
	NCI	1.74			
Normal	Innova CCT	1.77	0.03	-0.03 to 0.10	= .27
	NCI	1.74			
S	Konan CCT-HD®	0.86	-0.19	-0.25 to -	< .001
	Innova CCT	1.04		0.09	
S	Konan CCT-HD®	0.86	0.06	-0.03 to 0.15	= .18
	NCI	0.80			
S	Innova CCT	1.04	0.23	.219 to0.250	< .001
	NCI	0.80			

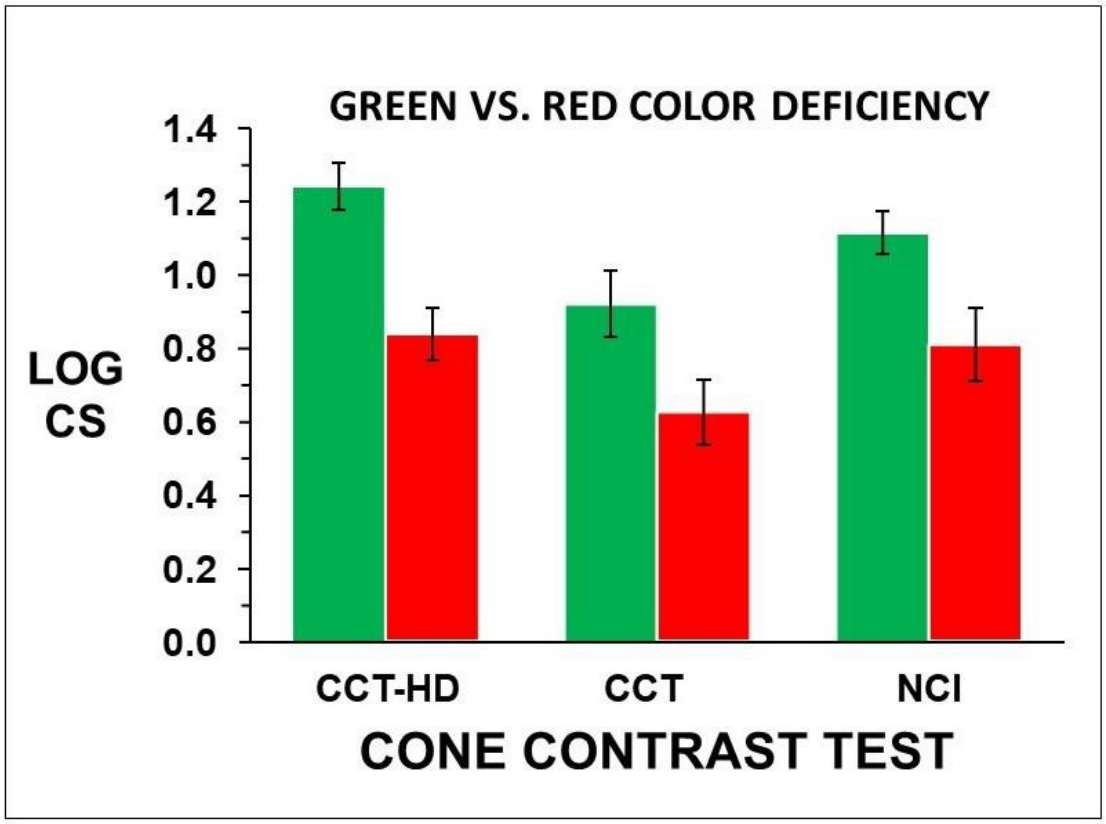

Figure 29. Comparison of Deutan and Protan Mean Log CS (± 2 SE). Across tests, protans scored lower than deutans.

Independent t-tests were conducted on the deutans normal L cone and the CVNs L cones followed by the protan's normal M cone and the CVNs M cone. Results are show in Table 4.

Table 4. Independent T-Test Results Between CVD Normal Cone and CVN Corresponding Cone.

Cone Type	Test	CVD Type/CVN	Mean	Mean Difference	95% CI	*P* Value
L	Konan CCT-HD®	Deutan	1.82	0.27	.211 to0.337	< .001
		CVN	2.09			
L	Innova CCT	Deutan CVN	1.76	0.12	.043 to0.188	< .003
			1.88			
L	NCI	Deutan CVN	1.73	0.12	.044 to0.196	< .004
			1.85			
M	Konan CCT-HD®	Protan	1.75	0.298	.217 to0.382	< .001
		CVN	2.05			
M	Innova CCT	ProtanCVN	1.80	0.12	-0.015 to	= 0.07
			1.92		0.259	
M	NCI	ProtanCVN	1.84	0.07	.014 to0.129	< .02
			1.77			

All three tests showed 100% sensitivity for detection and identification of CVD and type. In CVNs all tests showed 100% specificity for confirming normal L and M cone CS, but Konan CCT-HD® showed 96% specificity in CVNs and 92% in CVDs for L cone CS.

Discussion

Our findings indicate no significant differences between sensitivity of the three computer-based tests to detect the presence and type of CVD. All CVDs showed scores <75 in each eye on all three tests indicating 100% sensitivity. All three tests identified normal color

vision in CVN subjects. Based on these criteria, all three tests are suitable for occupational application for detection of hereditary CVD if administered appropriately. Testing subjects at incorrect distances or selecting a 'distance' setting on the test rather than the 'near' setting would produce larger letters and provide incorrect results. In other words, specifying the wrong test distance in each system could contribute to systematic error which, while avoided in this study, may be contributory to differences reported when using these tests occupationally. However, in what follows, we focus on specific differences between tests to identify strengths and weaknesses which are minimal for most occupational scenarios but become more relevant for acquired CVD.

The Konan CCT-HD® system yielded higher values for L and M cone CS, attributable to its finer gradation in contrast steps and psi method of achieving a threshold which is a validated adaptive approach (each response depends on subject's prior response) to achieve a reliable threshold as well as a standard error to quantify response variability over time.[55] Furthermore, the contrasts used in the Konan CCT-HD® were lower than the Innova CCT and the NCI which may have contributed to the lower thresholds (e.g., higher log CS). The Konan CCT-HD®, and NCI, also utilizes a higher luminance, approximately 100 cd/m^2, which may contribute to the higher log CS value. The original USFASAM CRT based CCT used a grey background luminance of 25 cd/m^2. The Innova CCT with the extended contrast range also yielded thresholds and it is conceivable that the lesser gradation of contrasts on the Innova CCT contributed to lower thresholds. Although unlikely to impose a substantial effect, the Innova CCT and Konan CCT-HD® used different algorithms. The Innova CCT used a 10-alternative forced choice approach adaptive staircase while the Konan CCT-HD® used a 4-alternative forced choice adaptive staircase. In other words, the Konan CCT-HD® may have yielded higher

Konan CCT-HD® threshold due to greater opportunity for guessing. It is noteworthy that higher B cone scores were achieved with the modified Innova CCT contrast scale compared to the Konan CCT-HD®. This is most likely due to the larger character size used on the Innova CCT to render its letter size near the peak of the S cone CS function.[47,59,60] Last, differences in tasks may have contributed to different log CS values. The Konan CCT-HD® and NCI uses a detection task (i.e., find the location of the gap in the Landolt C) while the Innova CCT uses a higher order letter recognition task.

Each test reported on in this study provides a valid and reliable log CS score (or point score) that can assist determining suitability for visually demanding occupations. Currently, the military services utilize a 100-point scale to make this determination. Initially the passing score was 75 on the original Innova CCT but was lowered to 55 and there is no requirement for administering or passing the S cone test. The modified Innova CCT and NCI version scores of 75 and 55 correspond to log CS values of 1.65 and 1.45, respectively, while the Konan CCT-HD® uses a passing score of 1.45 log CS for scores of 55. Values for each test targeted contrast levels are shown, but the reader should be aware that each display may differ slightly based on targeted values achieved using a narrow tolerance during calibration. Furthermore, protans who score lower may be put at a disadvantage if a passing score is set at 55.Table 5 shows 75 and 55 log CS scores for each system.

Table 5. Comparison of log CS values for 75 and 55 scores.

100-Point Score	Cone Type	Konan CCT-HD® Log CS	Innova CCT Log CS	NCI Log CS
75	L	1.67	1.65	1.63
55	L	1.47	1.35	1.30
75	M	1.65	1.65	1.63
55	M	1.45	1.35	1.30

The log CS values across the systems at 100-point scores of 75 and 55 are similar except for Konan CCT-HD® L cone score of 55 which equates to a log CS of 1.47. Whether or not the scores of 75 and 55 are operationally suitable needs further investigation though studies have shown that that the standard score of 75 does not equate to operational performance.[58] The United States Air Force Operational Based Vision Assessment Laboratory has worked toward linking color vision performance to operational performance.[61] The focus of their research is to fully understand how color vision and color vision degradation impact operational performance.[58,61,62]

It is conceivable that fatigue and effort level may have influenced our results since all three tests were conducted in one session in random order. However, this would be revealed as significant differences in CVNs and CVDs and these were not detected. In addition, practice or transference effects are possible but unlikely given the agreement between sensitivity and specificity, lower protan than deutan scores across all three tests, and the dissimilarity in exact

testing procedures. From an operational perspective, the age range used in this study is in line with other studies using subjects of suitable military occupation training age.[17,63] However, caution should be applied for generalizing the results for clinical setting due to the young mean

age of the study participants.[63]

Overall, each test provides reliable classification of CVN and CVD status. The log CS values corresponding to the cutoff scores of 75 and 55 are comparable across tests. Additional studies determining if there is agreement between the three tests and their corresponding log CS and cutoff scores is warranted. Further research on these three computerized color contrast sensitivity tests in single or multi-test protocols would be useful.[50,64]

Study #2: Sensitivity and Specificity of a New Signal Light Test

Introduction

The purpose of this research was to establish the sensitivity and specificity a New Signal Light Test (NSLT) for the railway industry and to determine if computerized color vision test can predict the outcome of the practical field test and thereby be a suitable screening tool for the railway industry. The history of color vision testing within the railway industry will be briefly explored starting with the famous crash in 1875 at Lagerlunda, Sweden.[65] A more recent event, the railway crash near Goodwell, OK and the actual catalyst for the present research, will be discussed along with the National Transportation Safety Boards (NTSB) and the Federal Railroad Association (FRA) response to the causes of the crash. Pertinent literature on the effects of test distance, cue removal, and reduced visual acuity on practical and lantern test performance is explored.

History of Color Vision Testing in Railway Industry

Interest in defective color vision within the railway industry started in the mid-19th century. Wilson began investigating the propensity of color-blindness among his students and the impact such a deficiency would have on occupations requiring the ability to differentiate between color signals.[66] While several notable physicians in both England and continental

Europe were exploring color vision deficiency within the railway industry, it was not until an accident at Lagerlunda, Sweden that testing for color vision and excluding individuals with color confusion gained a foothold in the industry.[67] In November of 1875, two passenger trains crashed on an estate near Lagerlunda, Sweden. The events of that evening which led to the fatal crash have been explored extensively, and it has not been proven beyond a doubt that color vision deficiency was to blame.[67] The fatal accident however provided an opportunity for ophthalmologist Frithiof Holmgren to suggest that color vision deficiency was one of thecauses for the crash, to push for color vision requirements within the railway industry, and to introduce his wool test as the method of choice for color vision screening (Figure 30).[67,68]

Lantern tests were developed late 19th century to the early 20th century as a replacement for the wool tests. Most of the early lanterns were cylindrical in shape, a rotating wheel with different colors filters that were illuminated by oil lantern or electricity.[70] Since then, several lantern tests, varying by aperture configuration and size, filters, and colors, have been developed and utilized to assess employees' color vision occupational suitability.[39,71,72] Lantern tests have evolved to more closely resemble the signal lights colors utilized in occupational environments shifting from incandescent light (IC) to light emitting diodes (LED) lights to reflect the changes occurring in railway signal upgrades.[39] The Holmes-Wright A lantern (HWA) was originally developed for utilization in the aviation industry in the late 1970s.[72] For the last twenty years, the test has been a staple in the transportation industry and has been assessed for suitability within the railroad industry.[73] It is important that the colors used in the test are the same as those used by the railway and fall on the same chromaticity coordinates. Hovis and Oliphant tested the HWA for its suitability as a railway screening test due to its lack of face validity because it did not utilize signal colors that fall on the chromaticity coordinates used by the railway system.[73,74]

The experimental set up utilized a simulated field test as a comparison to the HWA. Both were found to be difficult tests for color vision deficients, but the HWA did show a 5% false negative rate. While it has been used in the railway industry, the reason was due to availability and not necessarily its agreement with occupational tasks.[75]

Figure 30. Holmgren's colored wool test for color blindness.[69] Subjects were asked to identify the color of the wool yarn.

In 1996, a fatal train crash in New Jersey was the result of an engineer's acquired color deficiency.[76] The FRA updated color vision testing standards and outlined screening tests which required normal color vision to pass.[77,78] The response from Hovis and Oliphant was to develop a

Canadian National Railway lantern test (CNLAN) that is suitable for a railway occupation screening test.[75] The research showed sensitivity of 100% and specificity of 97%. More importantly, it utilized signal colors representative of wayside signals used on the railway establishing face validity.

Between 2000 and 2005, the RailCorp Lantern (RL), an LED simulation of railway signals, was developed in Australia. A retrospective study was conducted to compare the performance of the RL against the Farnsworth Lantern (FL) and found that the RL was more adept at passing individuals who could accurately identify railway signals while at the same time detecting most individuals with color vision deficiency.[40] The Railway LED Lantern Test (RLLT), another railway specific test, was a practical test utilizing modern railway LED lights and was found be an easy test to administer that is applicable to the railway industry.[39]

The advantage of the CNLAN, RLLT and the RL is that they are based on actual railway practice, albeit in different countries. Furthermore, both lanterns are considered appropriate as a test that meets CIE Color Vision Standard 1.[43] The lanterns have shown to be comparable to other lanterns in use[42] and while the lanterns are considered practical tests, they fail to meet one important criteria of a practical field test and that is test distance.[44,79] Nevertheless, the literature on lantern tests provide us with valuable information on how color vision deficient (CVDs) will perform when asked to identify signal lights.

Purpose of Current Study

More recent events have prompted the current investigation reported on in this chapter. On June 24, 2012, two trains were involved in a head-on collision near Goodwell, OK. The accident was fatal, and damages were estimated to be approximately $14.8 million.[78] The NTSB investigated and discovered that one of the engineers had degraded visual acuity in addition to an

acquired color vision deficiency. These conditions, in addition to the timing of recertification testing, contributed to the inability to recognize the railway signals. More importantly, the visual testing the engineer had undergone for recertification had not followed the prescribed visual testing protocols. The field test utilized had not been validated.

This incident prompted the FRA to release a document outlining the recommended practices for color vision field tests' design and administration in addition to expectations of the scientific vision tests used for initial evaluation and screening purposes.[79] For clarification, there are numerous lantern tests that are utilized as simulated field tests. These are not the same as an actual field test which is defined as a test performed under conditions that are similar to real-world working conditions. Table 6 outlines the best practices for a field test.

Table 6. Best Practices of a Field Test.[79]

Best Practices
1.Standardized test procedures. 2.The testing officer is qualified to supervise individuals taking field test. 3.Testing officer qualifies and meets medical standards. 4.Test results are recorded during testing. 5.All relevant information is recorded. 6.Testing officer confirms data was accurately recorded. 7.Examinee is informed of testing procedures prior to test either verbally or written. 8.Examinee should be allowed to wear prescribed corrective lens wear (i.e., contact lenses or spectacles). 9.No chromatic lenses should be worn during testing. 10.Examinee's vision status is to be established and determined if stable or deteriorating. 11.The field test should be valid, reliable, and be similar to real world working conditions.

Figure 31. New Signal Light Test. The signal light on top of the pole rotates to displayeither a red light (shown above), green light, white light, or yellow light.

The NSLT was designed to be administered outdoors at the actual distance railway employees are expected to correctly identify the color of a wayside signal which is at a position of 1320 feetor ¼ of a mile. The size of the stimulus lights are replicas of those used on the railway system.

The size of the stimulus light was eight inches in diameter, and the angular extent was calculatedas follows:

Stimulus size = 8” x 1 ft/12” = 0.667 ft

Test distance = 5280 ft/mile; 5280 ft/4 = 1320 ft

Angle in radians = $\tan^{-1}$ (0.667 ft/1320 ft) = 5.053 x 10^{-4} radians

Angle in degrees = 180 degrees/π rads x 5.053 x 10^{-4} radians = 0.02985 degrees0.02895 degrees x 60 minutes/1 degree = 1.74 minutes of arc

Evaluating the NSLT based on its physical description alone partially satisfies the recommendations that the test equipment is a replica of signal lights found on the railway and that the test is administered at the longest distance expected to identify said signal. To take the FRA's recommendation a step further, the International Committee on Illumination (CIE) provided specific guidance when developing and implementing a practical test like the NSLT (listed in Table 4).[44] The first criterion is that the signal lights should be replicas of those found in the real-world and on the color confusion lines of CVD. A comparison conducted on the NSLT showed there were differences in brightness, but not luminance, between the IC fielded railway lights and the LED fielded railway lights.[80]

Table 7. CIE Seven Principles to Developing a Practical Test[44]

Seven Principles
1.Colors used in this the test should be the same as those encountered in practice AND lie on color confusion lines of CVD 2.Testing distance should occur at the longest distance expected to encounter in real world practice 3.Intensity of the signal lights should be at the lowest levels encountered in practice 4.Color cues must be removed unless they are always encountered in practice 5.A minimum of five (5) repeated trials for each color should be provided 6.Detailed administration procedures must be developed and followed 7.The test must be validated

The FRA also specified that scientific tests utilized as screening tests must be validated and determined reliable through rigorous testing with a report of the findings published in a peer-reviewed scientific journal. Cole and Vingrys and CIE further noted that a validation requirement for a lantern is that it must pass color vision normals.[44,72]

The primary focus of the current study was to establish the sensitivity and specificity for the NSLT. In addition to sensitivity and specificity, the research sought to determine if the cone contrast test (CCT, Innova Systems, Inc.) can predict the outcome of the NSLT. Additional measures such as testing distance, level of vision, and use of backgrounds were explored.

Methodology

Subjects

Subjects were recruited over a two-year period. Participants (n = 150) were recruited from the University of the Incarnate Word (UIW) and the Rosenberg School of Optometry (RSO) students, staff, faculty, administrators, patients, and colleagues/family members. Color vision status (i.e., normal or deficient) was confirmed by the 24-Plate Ishihara pseudo-isochromatic plate (PIP) test. Exclusion criteria included history of ocular disease or trauma, neurological disease, or systemic disease not controlled medically. Each subject was provided written informed consent, and our protocol was approved by the UIW Institutional Review Board (IRB).

Procedures

All subjects completed an outdoor lantern test and a series of clinical vision tests. The indoor tests included the Ishihara PIP (Precision Vision, precision-vision.com), anomaloscope (Oculus Inc., oculus.de/us/frontpage/) and Innova CCT (Innova Systems, innovasystemsusa.com). All tests were completed with best corrected visual acuity. The order of

which the tests were completed was randomized. All indoor tests were administered according to standard protocols and conducted monocularly with right and left eyes tested.

The outdoor test was performed binocularly. A verbal description of the NSLT was provided followed by a signal light demonstration of two same-colored lights (e.g., red/red) or a signal light demonstration of the four different colored lights (red/green/yellow/white). After the demonstration, the test—consisting of 20 trials with five presentations of each of the four colored signal lights—was administered. There were five separate randomized schedules which were alternated between subjects. The NSLT remained on for three seconds, and the subject was required to verbally identify each colored signal light within five seconds. If a subject missed one trial, the subject failed the test. To determine the effects of distance, signal light cover, and blur on test performance, subsets of the sample were asked to repeat the signal light test. A subset of the sample (n = 13) who failed the NSLT were retested at 1000 feet. Another subset of the sample (n = 15) retested with the NSLT placed under a canopy. A third subset (n = 13) was blurred to 20/40 and tested.

Statistical Analysis

Descriptive statistics describing the population were conducted. Paired-samples t-tests were conducted on the clinical tests to determine if there was a significant difference between right and left eyes. Sensitivity for the NSLT was calculated by using the following equations:

$Sensitivity = A/(A+B)$

Where: A = True Positives (TP), B = False Negatives (FN)

$Specificity = C/(C+D)$

Where: C = True Negatives (TN), D = False Positives (FP)

The proportion of pass/fail scores on the NSLT were compared between testing at ¼ mile

and 1000 ft. Proportions of pass/fail scores were also compared between testing with or withouta canopy and between testing without induced blur (i.e., VA = 20/20) or with induced blur (i.e., VA = 20/40). Differences in proportions were analyzed using McNemar's test.[81] Linear regression was used to determine if abnormal CCT scores can predict performance on the outdoor signal light test.

Results

Out of 150 subjects tested, 116 subjects (Mean age 31.98 ± 13.12, 42 Males, 74 Females) had normal color vision, one subject (female) with possible early glaucoma or optic nerve disease was excluded from analysis, and 35 subjects (Mean age 32.64 ± 12.99, 34 males, 1 female) were diagnosed with hereditary color deficiency. Of the 35 CVDs, ten had a protan deficiency and twenty-five had deutan deficiencies.

Original Protocol

The first 70 subjects, were all CVNs and were tested using the original protocol which demonstrated two same-colored lights prior to the test and showed a high failure rate of 25% (75% specificity). Sensitivity could not be calculated because no CVDs had been tested underthe two same-colored light protocol.

Thirteen subjects classified as CVNs who failed the initial test at ¼ mile retested at 1000 feet. On the retest at 1000 feet, an exact McNemar's test determined that the difference in proportion of pass/fail scores was statistically significant, $P = .001$. Out of 13 subjects who failed at the ¼ mile, 92% (i.e., 12 of 13) passed at 1000 feet. However, this result likely reflected familiarity of the light colors from the prior test at ¼ mile.

Fifteen subjects classified as CVNs were asked to repeat the test with the NSLT placed underneath a canopy. On the initial test without a canopy, 87% (i.e., 13/15) passed the test and

with the canopy, 87% passed the test. An exact McNemar's test determined there was no statistically significant difference between canopy/no canopy conditions ($P = 1.00$). The two subjects that failed without the canopy passed with the canopy.

Thirteen subjects classified as CVNs were tested with their vision at 20/20 and were blurred to 20/40 for a retest. At 20/20, 100% of the subjects passed the test. At 20/40, 92% passed the test. An exact McNemar's test determined that there was no statistically significant difference between the blur/no-blur conditions ($P = 1.00$). Since the railroad standard is a minimum VA of 20/40, individuals with 20/40 vision would be expected to pass the test.

Modified Protocol

Procedures were modified based on the high failure rate of the original protocol to demonstrate two same-colored lights. The protocol was modified to demonstrate four different colored lights prior to test initiation. To determine if the change in the protocol was viable, CVN subjects (n = 21) and CVD subjects (n = 10) were administered the NSLT under the new protocol which demonstrated four different colored lights prior to commencement of the test. The sensitivity and specificity were then calculated using the data from the 31 subjects. The sensitivity for the NSLT when four practice signals were administered was: 19/(19+2) = 90%. The specificity for the NSLT when four practice signal lights are administered was: 9/(9+1) = 90%. Since the new procedures improved the pass/fail rate, the outdoor testing continued with the new protocol. All remaining CVNs (n = 25) passed the lantern test without any errors (i.e., TP = 25, FP = 0). All remaining CVDs (n = 25) failed the lantern test (i.e., TN = 25, FN = 0). The sensitivity for the lantern test when four practice signal lights were administered was: 25/(25+0) = 100%. The specificity for the lantern test when four practice signal lights are administered was: 25/(25+0) = 100%.

Predictive Analysis

The right and left eye were equivalent across tests for CVDs (F = 0.21, *P* = .89). Hence the mean of right and left eye CVD scores (e.g., L cone score for protans, M cone score for deutans) from the Innova CCT were used to determine if cone contrast sensitivity can predict performance on the NSLT. Regression analysis was conducted on the difference between the throughput of the normal and abnormal cones. Throughput was calculated as log CS/response time. The regression showed that the Innova CCT abnormal cone scores predict NSLT scores, r^2 = 0.26, *P* = .009; Fig. 32). While the r^2 value is relatively low (CCT can explain only 25% of the variance in the NSLT), an analysis of the residuals plotted against the NSLT scores showed no discernable pattern, only random variation across the range of scores. It should be noted that the two tests measure different aspects of color vision. Currently, our laboratory has developed and is validating a new color vision test which combines L, M, S and BW cone contrast sensitivity thresholds along with the accuracy of color naming—an important component of signal light identification. It is anticipated that this new test will be more predictive of signal light performance and related occupational tasks.

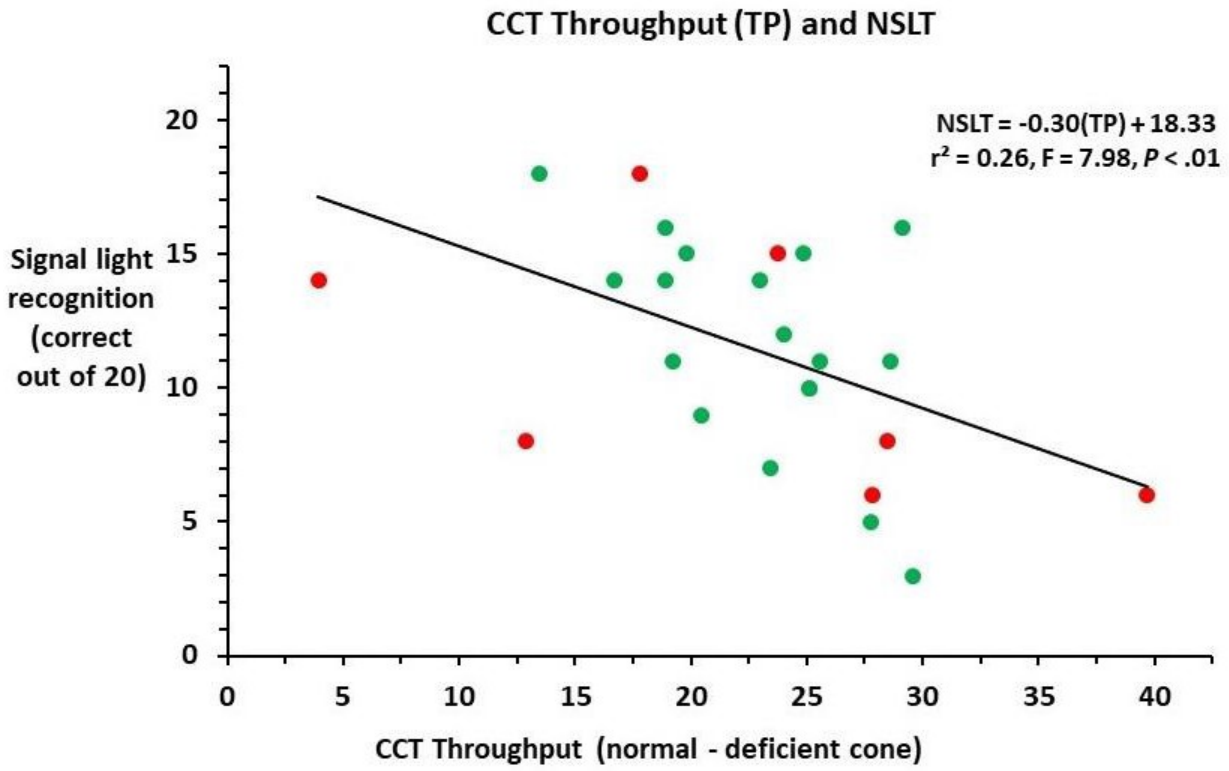

Figure 32. CCT throughput predicts NSLT outcome. Red dots represent subjects withprotan deficiency and green dots represent subjects with deutan deficiency.

An independent-samples t-test was run to determine the differences between protan and deutan across railway lantern scores. There was no statistically significant difference between protan (11.00 ± 3.42) and deutan (11.61 ± 4.51) NSLT scores (*P* =.72). Independent-samples t-tests were run on abnormal, normal and S cone 100-point scores for the Innova CCT. For the Innova CCT system, mean abnormal 100-point scores for protan (10.36 ± 7.13) were lower than deutan (29.58 ± 13.26), a statistically significant difference of -19.23, (95% CI, -30.26 to -8.20, *P* = .001). There was no significant difference between the mean normal cone scores for protan (78.57 ± 7.05) and deutan (79.67 ± 4.04) and no significant difference between S cone scores for protan (97.14 ± 3.66) and deutan (95.59 ± 5.41). For the CCT system, mean abnormal cone log CS for protan (0.63 ± 0.12) were lower than deutan (0.92 ± 0.05), a statistically significant difference of -0.29, (95% CI, -0.46 to -0.14, *P* = .001). There was no significant difference

between the normal cone log CS for protan (1.70 ± 0.10) or deutan (1.67 ± 0.17) and the S cone log CS for protan (1.03 ± 0.06) or deutan (1.00 ± 0.08).

Discussion

There was a high failure rate of CVNs when only two same-colored demonstration lights were shown prior to the start of the test. After consideration, it was thought this high failure rate was due to the unfamiliarity of the test subjects with the signal lights. The change of administration procedures from two same-colored demonstration lights to four different colored demonstration lights increased the sensitivity of the lantern test markedly from 76 to 90 percent in the first cohort. Modifying test procedures to increase the efficacy of the test is not uncommon. Cole, Lian, and Lakkis found that it would be prudent to administer several runs on a lantern test to mitigate the 10% pass rate of CVDs on a one trial run test.[82] More stringent pass/fail criteria have also been recommended since lantern tests have not necessarily been reflective of real world signal lights.[83]

The change in administrative procedures increased the sensitivity and specificity of the NSLT to 100% for both measures. For the final cohort, the new procedures provide subjects the ability to familiarize themselves with the signal lights. Furthermore, NSLT will fail CVDs. Previous studies implementing changes in the study protocol focused on multiple practice and/or test runs.[84,85] The repeat data from the present study revealed a significant difference in pass rates for CVNs, but this was for participants who were only shown two same colored demonstration signal lights. Additional studies utilizing CVDs to determine the effect of repeat tests on pass fail rates for the NSLT are warranted.

A minimum level of visual acuity has been correlated with color vision test outcome.[86] The results of the current study showed no effect of blur on pass/fail rates for CVNs. This does

not necessarily mean the NSLT is tolerant to blur or lower levels of visual acuity. Other studies investigating the correlation of blur/lower VA to color vision test outcome had significantly reduced levels of VA ranging between 20/55 and 20/180.[86,87] Studies imposing significantly greater blur in both CVNs and CVDs would be necessary since weather conditions can significantly reduce VA.

As expected, testing distance made a significant impact on pass rates. Previous research with CVDs have shown that shorter testing distances improves pass rates on lantern tests.[88,89] Lantern test results have been found to improve at shorter distances indicating suitability for occupations that do not require long distance color vision accuracy. Hovis and Ramaswamy investigated the effect of distance on lantern tests and revealed improved pass rates with shorter distances.[88] Utilizing test distances of 4.6 and 2.3 m and a subject pool of CVDs, they showed a significant decrease in the number of errors when test distance was shortened and an 11% increase in the number who passed at a shorter distance. Almustanyir and Hovis recently extended this research, focusing on even shorter distances.[89] The results showed that CVDs, given more time and shorter distances, could accurately name colors thereby being suitable candidates for occupations not requiring long distance color accuracy. However, the current sample who were tested at shorter distances comprised only CVNs. Therefore, any comparisonof the current results to previous studies would be tenuous.

Several studies have investigated whether clinical vision tests can be predictive of lantern test outcomes with mixed results. Almustanyir and Hovis found that failure on the Farnsworth Munsell D15 (FM-D15) or the ColorDX D15 were predictive of a fail on the CNLAN at the distance of 4.6 m[90] though Cole and Maddocks study concluded that neither the FM D15 nor the Nagel Anomaloscope was predictive of the HWA lantern.[91] The fact they were testing two

different lanterns, one which was designed to be representative of the railway (i.e., CNLan), should be taken into account. Almustanyir, Hovis, and Glaholt later found the CAD, CCVT, and OCCT were predictive of HWA outcome.[48] The Ishihara has also been found to be predictive of the FL.[92] The current regression analysis revealed that the abnormal Innova CCT 100-point score was the only clinical test predictive of the railway outcome. Because of the small sample, additional testing is warranted to determine if the predictive capabilities hold over a wider range of subjects.

Limitations of this study include possible fatigue on the part of the subject. The within-subjects design required the subject to complete several visual tests in addition to the outdoor signal light test. Research has shown that fatigue affects color vision.[93,94] It is plausible that test results were impacted by the number of tests the subject was required to complete. A post-hoc analysis of test order (outdoor versus indoor) on CVN pass rates or a z-score comparison of color vision tests since they were administered sequentially may provide interesting information. The current study did not investigate the association between VA and pass/fail rates of the outdoor and indoor tests and the blur imposed reduced VA to only 20/40. Understanding these associations and conducting studies with significantly more blur is warranted. An additional limitation is the small number of CVDs included in the study. Predictive analysis with a larger CVD cohort is required to definitively assess the predictive capabilities of the computerized color vision tests included in this study.

In conclusion, the railway signal light has 100% sensitivity and specificity, meeting the criteria of a practical field test as defined by the FRA and CIE.[44,79] Repeat trials along with displaying all four signal lights prior to test administration is recommended to eliminate false negatives. The CCT has proven predictive of the railway signal outcome but further research is

required to bolster this assertion.

Study #3: Exceptional Hue Discrimination in Jewelry Appraisers

Introduction

The field of jewelry appraising requires discrimination between differences in gemstone hue by observation with the naked eye, supplemented by spectrometers, microscopes, and more commonly a handheld loupe for magnification. Different levels of illumination are utilized ranging from daylight equivalent fluorescent light sources, light emitting diodes (LED), to varying amounts of ultra-violet light (UV) within ambient sources. Auxiliary equipment help the appraiser to identify different facets and hues within the gemstone to optimize their judgement of valuation.[95] Hence, visual inspection of gemstones is complex due to the optical properties of color coverage, brilliance, and dispersion all of which can impact the hue of the stone.[96] Jewelry appraising does not have minimum vision or color vision standards so it is plausible an individual with mild color vision deficiency can be certified by National Association of Jewelry Appraisers (NAJA) (appraisalfoundation.sharefile.com/share/view/se88e19d655740efb).[97]

NAJA certification requires that the applicant complete the Farnsworth-Munsell 100 Hue test (FM-100)[98] administered under the supervision of an optometrist or ophthalmologist; re-certification every five years requires that the FM-100 be repeated. However, NAJA does not specify a passing criterion for the FM-100 and allows the clinician to make that decision. We elected to use a total error score (TES) of ≤ 100 since a score between 16 and 100 is considered within normal limits, while 0 to 16 is considered superior.[99] The TES is the sum of the number of signal transpositions of color caps. Historically, a score of ≤ 100 has been used as passing military entities as well (J Rabin, O.D., Ph.D., oral communication, May 25, 2021). At this time, no other test can be substituted for the FM-100. The test can be time consuming to complete,

difficult to score, influenced by type of illumination and subject to practice effects. Farnsworth was unclear about how to count the end caps and different scoring methods regarding box end caps have been developed.[98,100] Lower illumination levels have been associated with higher FM-100 TES.[101,102] FM-100 results can also improve significantly with continuous practice, although it may be limited according to the administrative technique utilized such as test timing, lighting, and viewing conditions (i.e., monocular vs. binocular).[103,104] Other scoring issues center on lack of examiner training as well as misinterpretation of data due to unfamiliarity with normative data.[105,106] Furthermore, while the manual version is time intensive, computer based versions require calibration to achieve accurate hue rendition.[107,108]

Other color vison tests, such as the Innova Cone Contrast Test (Innova CCT, Innova Systems Inc., innovasystemsusa.com), may provide a potential alternative to the FM-100.[60] The Innova CCT is a computer-based test which presents letters visible only to L, M, or S cones. The L and M cone stimulus uses a 1.22 log MAR (6/100) letter size while the S cone letters are 1.30 log MAR (6/120) to account for the lower spatial resolution of the S cone pathway. A letter appears briefly (5 seconds) in the center of the display and the subject uses a mouse to select the letter seen from the adjacent matching display. An adaptive staircase program determines the lowest detectable L, M, and S cone contrasts seen as well as average response times. The Innova CCT has proved comparable to the anomaloscope for detection of type and severity of hereditary CVD[47] as well as acquired CVD associated with ocular systemic and neurologic disease.[54] The purpose of this study was to determine if the Innova CCT, a more rapid computer-based test which provides quantitative cone sensitivity scores, predicts performance on the FM-100, thereby providing a potential alternative test to the FM-100 for initial and periodic screening of color vision screening of jewelry appraisers.

Methodology

Subjects

NAJA members who required color vision certification were invited to participate in our 1-day study to assess performance on the Ishihara test, FM-100, Lanthony Desaturated D-15 (desaturated D-15, Precision Vision, Inc., Woodstock, IL) and the Innova CCT. The Ishihara test was selected due to its high sensitivity for identifying hereditary CVD and has been used in conjunction with the FM-100 in prior NAJA testing.[38] Since the FM-100 and desaturated D-15 are both color arrangement tests, the desaturated D-15 may achieve a quantitative results in much less time and effort than the FM-100. Therefore, the Ishihara was used to establish normal color vision, and the desaturated D-15 was used as a potential surrogate for hue arrangement, as was the Innova CCT, a newer test offering cone thresholds that could potentially predict FM-100 scores.

All subjects provided written informed consent in accord with our institutional review board-approved protocol, and all data were collected in accordance with the Declaration of Helsinki and its revisions. The mean age for participants (n = 18) was 57 years (SD = 12.45) with a range of 34 to 76 years of age, and no subjects reported a history of ocular trauma or eye disease. Of the 18 subjects, four were male and 14 were female. Subjects were instructed to wear their habitual correction for near (if different from the distance correction) for all testing without any tinted lenses. Subjects were randomly assigned to start at one of the four color vision test stations (Ishihara, desaturated D-15, FM-100, and Innova CCT).

Procedures

The Innova CCT presents randomized, single letters in the center of a calibrated computer display that are visible to L, M, and S cones. The subject was asked to use a mouse to

select the letter seen from an adjacent matching display with the option of "PASS" if the letter cannot be recognized. A rapid, adaptive staircase is used to determine L, M and S cone letter recognition thresholds. Testing was conducted monocularly (right eye followed by left eye in accordance with the Innova CCT program) in a darkened room at the standard distance of 91.5 cm with the habitual correction. Since the Innova CCT is calibrated for monocular testing, we chose to administer it monocularly to avoid a potential ceiling effect, while binocular FM-100 Hue Testing was conducted in accordance with the normative data utilized in our comparative analysis.[105]

All subjects made no errors on the Ishihara test (14 of 14 correct; first 14 testable plates on the 24 Plate version), providing no evidence of hereditary CVD in our sample. All subjects passed the desaturated D-15 test (only one subject made 1 single-place transposition) indicating that this test provides an index of accurate color discrimination but cannot grade color ability within this limited sample of jewelry appraisers.

Statistical Analysis

Parametric regression analysis was used to determine if the Innova CCT predicted FM-100 TES and post-hoc paired t-tests were used to determine the relative contribution of L, M and S wavelength cone contrast sensitivity (CS). Two-sample t-testing was used to assess the hue discrimination differences between NAJA subjects and age-matched normative data published by Kinnear and Sahraie.[105]

Results

Paired t-tests showed no differences for L cone between right eyes (84.72) and left eyes (84.44), t(17) = 0.164, $P = .871$; for M cone between right eyes (81.11) and left eyes (mean = 81.68, SD = 8.74), t(17) = -0.287, $P = .777$; and S cone (94.17), t(17) = -1.03, $P = .317$). Innova

CCT scores and regression analyses showed that the higher of the two scores was most predictive of FM-100 TES. Post-hoc t-test analysis showed that only M and S cone CS were predictive of TES while L cone CS was non-significant (R^2 = .05). The model which yielded the most significant prediction of TES from Innova CCT utilized the average of the higher Innova CCT M and S cone score from each eye to predict TES ($F_{1,16}$ = 7.77, P = 0.01; r^2 = 0.33; Fig. 33). While the prediction of FM-100 from Innova CCT is significant, it accounts for only 33% of the variability in 100 scores, likely due to the limited sample size, addressed in the Discussion.

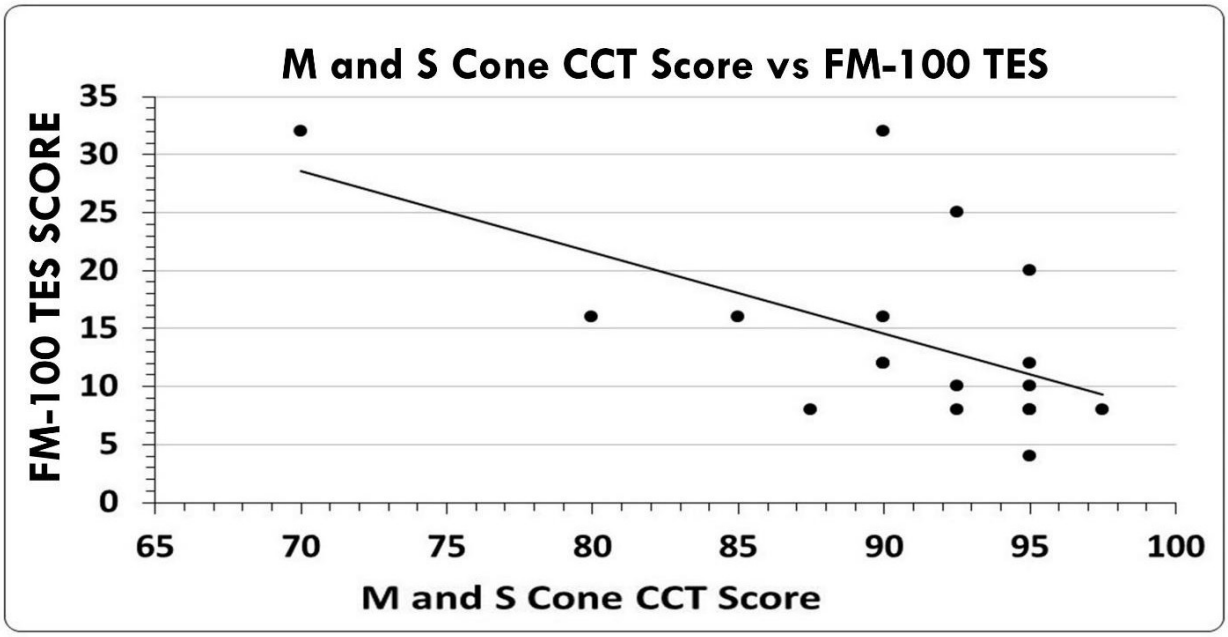

Figure 33. Average of M and S Cone CCT Scores Predict FM-100 TES. The CCTaccounts or 33% of the variability in the FM-100 scores.

The regression equation between Innova CCT and TES from the jewelry appraisers (TES = -0.70(CCT) + 77.86) was used to provide a preliminary estimate of Innova CCT passing score by using a TES score 3 standard deviations above the mean in our NAJA cohort [14.28 + 3(8.19) = 38.84]. Inserting this TES score into the regression equation yielded an Innova CCT score of 56. Since the Innova CCT is scored in 5-point intervals, an Innova CCT score of 60 or above would

be considered passing. Note that this estimate is preliminary given the small sample size.

There was no significant relationship between age and FM-100 TES scores in this sample (P = .079) though the trend was an increase in TES scores with an increase in age which is consistent with the literature.[9] Interestingly, 17 of 18 subjects had FM-100 TES scores well below the lower limit of age-matched normal values (Kinnear and Sahraie)[9]. One subject was at the lower limit of normal but still well below the mean (Figure 34). A two-sample t-test between the NAJA TES values and the lower limit of age-matched normals revealed a significantly lower mean (±SE) TES for the NAJA group (14.3 ± 1.9) compared to norms (59.1 ± 6.3) yielding a mean difference and 95% confidence interval (CI) of: 44.8, 95% CI 35.4 – 54.2, P < .001.

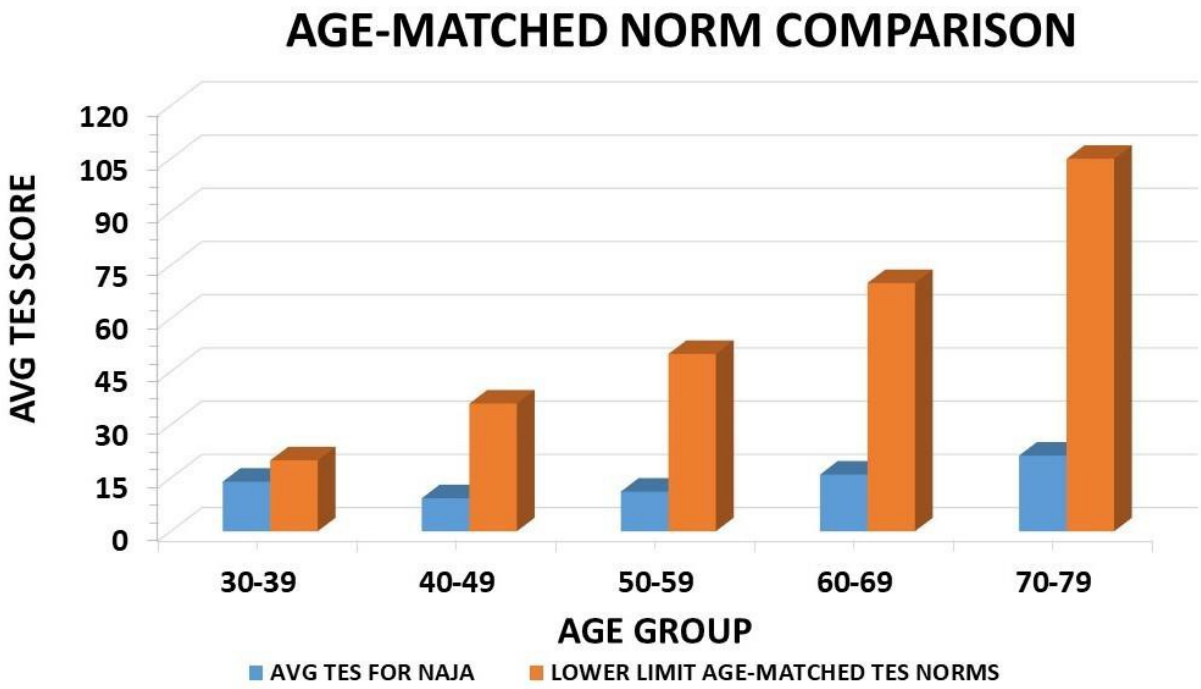

Figure 34. NAJA TES compared to Age-Matched Norms. A majority of the subjects had FM-100 scores well below the lower limit of age-matched TES norms.

Discussion

The results indicate that the Innova CCT may prove to be an effective substitute for the FM-100. Innova CCT scores were predictive of FM-100 scores though it was limited to M and S

cones. This is likely due to the importance of medium and short wavelengths to gemstone hue discrimination, although this may be gemstone dependent. The significant relation between M and S Innova CCT scores and FM-100 scores indicates the importance of M and S cone signals for hue discrimination necessary for accurate gemstone valuation. This is evident in Figure 35 which shows perception of a highly valued gemstone in normal, protanope, deuteranope and tritanope views. The protan and normal views are similar while deutan and tritan views appear different from the normal (high value) gemstone view, exemplifying the importance of M and S cone contrast and hue information for gemstone valuation.

Figure 35. Gemstone View in Normal, Protanopic, Deuteranopic, and Tritanopic Views. A gemstone is viewed in normal, protanopic, deuteranopic and tritanopic views emphasizing the importance of M and S cone input for accurate hue discrimination.[109]

The exceptional hue discrimination of jewelry appraisers indicated by their low total error scores could be a practice effect, a well-known factor of the FM-100. Significant improvement to

TES after several testing sessions have been found to last over several months.[103] It is plausible that the nature of jewelry appraising lends itself to a transferable skill when takingthe hue arrangement test. Another explanation could be that the career field draws individuals who have natural superior hue discrimination.

An alternative explanation to the jewelry appraiser's excellent performance on the FM-100 could be due to a highly practiced, reward-based repetition which is a tenant of perceptual learning. The principle of perceptual learning wherein repetition on specific tasks enhance performance and shifts the relative balance of brain serotonergic excitatory and GABAergic inhibitory activity possibly re-awakening latent synapses and/or formation of new synapses.[110,111] Indeed, perceptual learning has revealed improvements on various visual tasks such as visual and vernier acuity as well as stereo-acuity in adult amblyopic individuals.[112-114] Hence, latent cortical connections and/or new connections may be formed even in adulthood after "critical" periods of development. Such neuro-plasticity could explain the enhancement in hue perception with age following repeated, reward-based completion of critical tasks.

A primary limitation of this study is the small sample size (n = 18) making it untenable to state definitive conclusions about the efficacy of the Innova CCT as a FM-100 replacement, or the role of perceptual learning. Additional data from jewelry appraisers are needed to fully justify the use of the Innova CCT, supplemented by control data showing a correlation between the Innova CCT and FM-100 in non-appraisers. Control measures from non-appraisers also would better substantiate a possible role for perceptual learning vs. practice.[103] The lack of visual acuity (VA) measures also limits conclusions, since superior hue discrimination could be related to VA, though the large size (1.5 deg.) of FM-100 targets limits VA decrements as a significant factor and subjects reported optimal habitual correction for near. The number of years working

in the field was not determined for all subjects (though age served as a surrogate), limiting the ability our ability to offer conclusive evidence of perceptual learning.

Though the sample is small, one strength of the study was the participant's gender demographics (78% female) were similar to the national gender demographics of the jewelry appraiser business (68% female) according to the U.S. Bureau of Labor Statistics (https://www.bls.gov/cps/cpsaat18.htm).[115] The demographics of the sample and appraiser business bring forth the issue on whether or not there are gender differences in hue discrimination. Research has provided conflicting evidence on the subject ranging from no difference between the sexes on FM-100 scores to showing higher thresholds on red-green axis for female observers.[116,117]

An interesting follow on study would be to explore the differences between normal (CVNs) and protan views of gemstones to see if there is any significant difference between the two views. While additional testing on a larger group of subjects will be necessary to implement the Innova CCT as a replacement for the FM-100, NAJA may consider using Innova CCT results in locations where the FM-100 is unavailable and applying our derived passing score of 60 or above to achieve certification.

In this study, we have shown that the Innova CCT is predictive of performance on the FM-100 making it a potential alternative for color vision testing for jewelry appraisers especially in locations where the FM-100 is unavailable. However, the subject size was limited, and additional testing will be required to substantiate the use of the Innova CCT in place of the FM-100. In addition, the study was cross-sectional and therefore any correlation between enhanced hue discrimination and perceptual learning cannot be directly inferred. A longitudinal study investigating this connection would strengthen the argument. Further investigation into the

exceptional color vision of jewelry appraisers is required to determine if performing hue discrimination daily leads to perceptual learning thereby enhancing hue discrimination ability.

Study #4: Impact of Simulated Auto Displays on Visual Performance

Introduction

Visual and auditory distraction (cell phones, texting, displays) increase automobile accidents.[118] Studies have found secondary auditory tasks, such as cell phone use and texting negatively impact drivers vehicle control.[119] Other research has revealed a negative impact on peripheral target detection while engaging in distracted driving.[120] Distraction complexity has shown to impact visual scanning while driving.[121] Current research on distracted driving has focused on a variety of measures. Studies have been conducted on cell phones in a variety of configurations (i.e., handheld, hands-free) and have found hands-free to provide faster reaction times than hands-on[122] but our previous research has shown that visual performance is still negatively impaired during hands-free cell phone use.[45] More specifically, we showed increased response times to contrast sensitivity tests for both CVNs and CVDs. CVDs showed decreased sensitivity corresponding to their type of deficiency.

Cell phone use has also found to disrupt visual information encoding.[123] Strayer et al. found significant impacts to reaction time and that these impairments are due to cognitive workload.[124] Memory of objects was also found to be impacted by cell phone conversations.[125] A gold standard measurement of distraction is its impact on reaction time to situations such as slowing a driver's reaction to the car in front of them braking, introducing a significant safety risk.[126] Berg and Desseceker showed improved reaction time with the introduction of a auditory distraction though this could be an artifact of an adaptive behavior.[127]

While cell phone distraction has been a focus of major concern, automobile displays with

auditory cues delay performance but research on their visual distraction is lacking.[128,129] Current research on navigational devices have focused on improved capability versus papers maps.[130] Lee and Cheng found that driving performance was better with portable navigational devices than with on-board navigational devices especially when the portable device is located in the individual's useful field of view accompanied with auditory feedback.[131,132] Hence, navigational systems have been found to be extremely helpful to individuals with reduced visual acuity such as older drivers.[129,133] Nevertheless, auditory distraction has been found to negatively impact identification accuracy.[134] The purpose of this study is to expand on earlier research to determine how simulated automobile display with an auditory distraction impacts contrast sensitivity and response times.

Methodology

Subjects

Thirty-two participants (mean age 27 YO ± 5) were recruited from the University of the Incarnate Word (UIW) and the Rosenberg School of Optometry (RSO) students, staff, faculty, administrators, patients, and colleagues/family members. Twenty-four participants (10 males, 14 females) completed both the Innova CCT distraction task and the Mario-Cart Game distraction task. Thirty-two participants (12 males, 20 females) completed the Mario-Cart Game. Color vision status was confirmed by the Ishihara. Exclusion criteria included history of ocular disease, ocular trauma, neurological disease, or systemic disease not controlled medically. Each subject was provided written informed consent in accord with our IRB-approved protocol.

Procedures

For the first task, subjects were tested binocularly with the Innova CCT which measures cone-specific color contrast sensitivity (L, M, and S cone CS), black/white contrast sensitivity

(BW CS) and low contrast (6%) visual acuity (VA) on a calibrated Microsoft Surface display viewed in a dark room at 3 feet. Each subject was tested, in randomized order, with and without visual distraction from an iPad mini display immediately to the right of the Surface display. The iPad displayed an image of a roadway intersection with a symbol in one of four quadrants. During distraction, an auditory cue 'look' occurred every 10 sec. during which the subject was required to view the iPad and verbally identify the symbol and its intersection quadrant location while continuing to complete CS and VA tasks (Fig. 36). Outcomes included average response time to identify letters, CS and VA scores, and number of correct intersection symbol identifications with and without distraction.

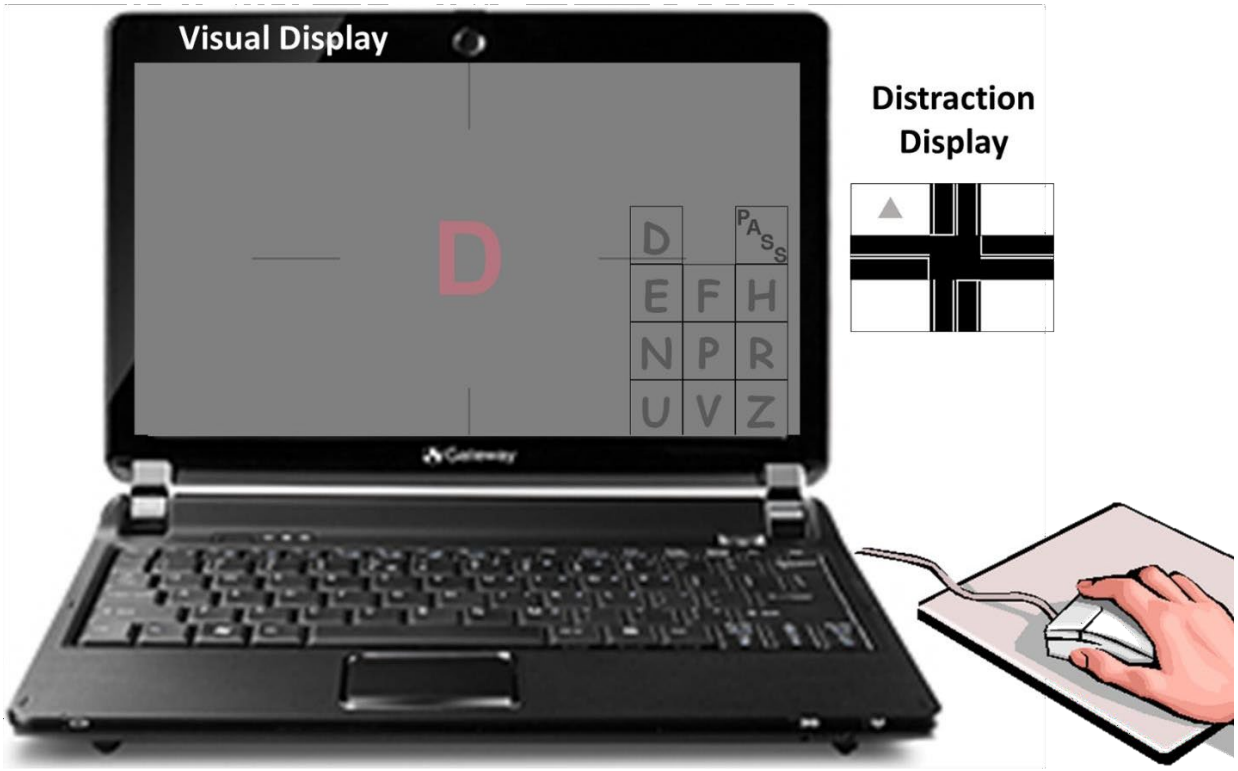

Figure 36. The main display for testing visual performance. The distraction display is shown at the left with a diagram of the simulated navigational display immediately to theright.

For the second task, subjects were asked to complete three rounds of a Mario Cart drivinggame

played on a Wi Station. Each subject was tested, in randomized order, with and without visual distraction from the iPad (Fig. 9) mini display immediately to the right of the Wi Play Station Game display. Outcomes included time to complete circuit and number of deviations off of the track.

Statistical Analysis

Repeated measures ANOVA was conducted to distraction effects on the Score, log CS, and average response time for chromatic contrast sensitivity (L, M, and S cone), contrast acuity, and achromatic contrast sensitivity. Post hoc paired t-tests were conducted. Paired t-tests were conducted to determine the effect of distraction on circuit completion time and number of deviations off course. The group in the first trial time was divided into without distraction and with distraction groups so independent t-test could be conducted to determine if distraction caused a significant difference in circuit completion time and number of deviations off course. This analysis was repeated for the second trial time. The participant data was again grouped in 1st trial versus 2nd trial, irrespective of distraction condition, to determine if there was an order effect on circuit completion time and number of deviations off course.

Results

Distraction Effects on First Task

A two-way repeated measures ANOVA was run to determine the effect of distraction on the scores of chromatic CS, visual acuity, and achromatic CS. Data are mean ± standard deviation, unless otherwise stated. There was a statistically significant difference between the scores of the without distraction and with distraction groups across chromatic CS, contrast acuity, and achromatic CS, $F(1, 4) = 9.51$, $P = .003$. Post-hoc paired t-tests revealed the without distraction group had a higher L cone contrast sensitivity scores (98.33 ± 3.19) than with

distraction group (95.63 ± 4.99), a statistically significant difference of 2.71 (95% CI, .65 to 4.77, *P* = .012). Though not statistically significant, the scores of all remaining measures showed higher values in the without distraction group than the with distraction group, Table 5.

Table 8. Score Differences Across Measures.

MEASURE	MEAN		DIFFERENCE	CONFIDENCE INTERVAL	
	Without	With		Lower	Upper
M Cone	96.25	94.38	1.88	-0.75	4.50
S Cone	99.58	98.96	0.63	-0.51	1.76
VA	96.04	95.42	0.63	-1.47	2.72
CS	99.90	99.59	0.30	-0.04	0.65

There was a statistically significant difference between the log CS without distraction and with distraction groups across chromatic CS, contrast acuity, and achromatic CS, F(1,4) = 9.58, *P* = .005. Post-hoc paired t-tests indicated the without distraction group had a higher red cone contrast sensitivity log CS (2.05 ± 0.061) than with distraction group (2.00 ± 0.086), a statistically significant difference of 0.05 (95% CI, 0.012 to 0.091, *P* = .012). Though not statistically significant, the scores of all remaining measures except for CA, showed slightly higher values for LogCS in the without distraction group than the with distraction group, Table 6.

Table 9. Log CS Differences Across Measures.

MEASURE	MEAN		DIFFERENCE	CONFIDENCE INTERVAL	
	Without	With		Lower	Upper
M Cone	2.06	2.02	0.04	-0.02	0.09
S Cone	1.06	1.05	0.01	-0.01	0.03
VA	0.15	0.15	0.00	-0.03	0.03
CS	2.05	2.04	0.01	-0.001	0.01

There was a statistically significant difference between response times without distraction and with distraction groups across chromatic CS, contrast acuity, and achromatic CS, $F(1,4) = 70.96$, $P = .001$ (Figure 37). Post-hoc paired t-tests results are shown in Table 10 and indicate that the increase is comparable to that with verbal distraction from simulated hands-free phone calls (mean: 0.30 sec).[45]

Table 10. Response Times Between Distraction Conditions.

Measure	Distraction Condition	Mean	Mean Difference	95% CI	*P* Value
L Cone CS	Without	1.63	-0.31	-0.44 to -0.180	< .001
	With	1.94			
ConeCS	Without	1.77	-0.18	-0.33 to -0.04	= .014
	With	1.96			
S Cone CS	Without	1.38	-0.21	-0.33 to -0.09	< .001
	With	1.59			
CA	Without	1.67	-0.25	-0.33 to -0.10	= .002
	With	1.92			
romaticCS	Without	1.33	-0.23	-0.34 to -0.12	< .001
	With	1.56			

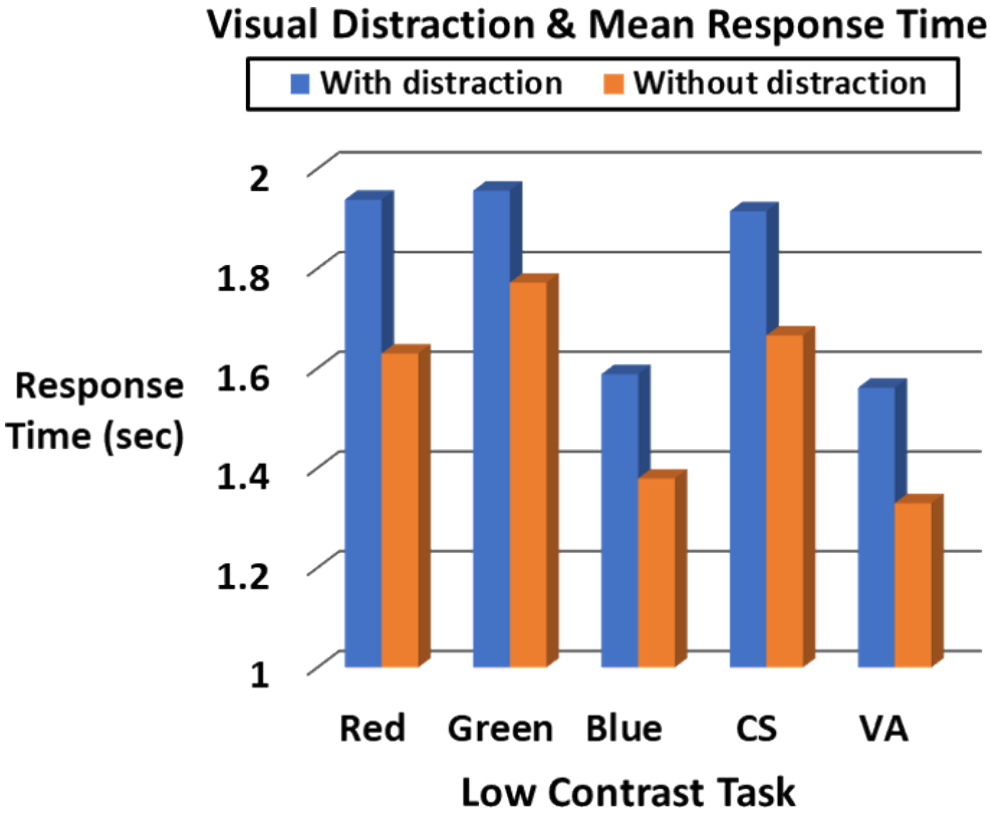

Figure 37. Mean response times for with and without visual distraction. All differenceswere highly significant ($P < .001$) confirming increased response time to detect targets when using a simulated navigation display.

Distraction Effect on Second Task

Paired t-tests indicated there was no statistically significant difference between the without distraction group (158.43 ± 41.93) and the with distraction group (154.26 ± 24.77) regarding course completion time. This held true for the number of course deviations. The without distraction group had slightly higher number of deviations off course (10.72 ± 9.68) than the with distraction group (10.13 ± 9.48) though the difference was not statistically significant.

When the 1st Trial group was divided into without distraction (n = 16) and with distraction (n = 16), the independent t-tests showed the without distraction group had a higher circuit completion time (170.13) than the with distraction group (154.19) though the difference was not statistically significant ($P = .30$). The number of deviations off course were higher in the

without distraction group (13.06) than the with distraction group (11.8) though the difference was not statistically significant (*P* = .73). The second trial group was divided into without distraction (n = 16) and with distraction (n = 16). The without distraction group had a higher circuit completion time (154.31) than the with distraction group (146.94) though the difference was not statistically significant (*P* = .35). The number of deviations off course were higher in the without distraction group (9.06) than the with distraction group (8.34) though the difference was not statistically significant (*P* = .83).

Order effect was also analyzed by paired t-tests (n = 32). The first trial group had a higher circuit completion time (162.16 ± 42.86) than the second trial group (150.63 ± 21.82), a statistically significant difference of 11.53 (95% CI, 2.34 to 20.73, *P* = .01). The first trial group also had higher course deviations (12.13 ± 9.75) than the second trial group (8.72 ± 9.04), a statistically significant difference of 3.41 (95% CI, 1.96 to 4.85, *P* = .001).

Discussion

Most research on the impact cell phone use has on drivers have primarily focused on reaction time.[119,135,136] Research has expanded to navigational devices showing improved driver performance.[130-132] However, recent studies have shown auditory input increases response times.[129] The current study was an extension of our previous research on cell phone distraction which focused on reaction time but also included ocular measurements of contrast sensitivity and contrast acuity.[45] Other studies with visual measurements have not included such measurements but focused on refractive blur and visual scanning.[129,137-139] Our current results showed that the only statistically significant difference across visual measures for score and log CS was L cone contrast sensitivity. While other visual measures were not statistically significant, the without distraction group did show higher contrast sensitivity across all measures with the exception for

contrast acuity log CS. It could be plausible that the L cone measurements are actually non-significant, reflecting a Type I error. Conversely, the non-significant findings across visual measures may reflect a Type II error resulting from insufficient power of the study. Irrespective of the cause, it would be prudent to conduct a follow-up study where there was a substantial increase in the number of subjects. Response time across all visual measures showed a significant difference between groups with the distraction group displaying higher response times. These results were expected since degraded response time is a widely known signature of distracted driving. [140,141] However, what was not expected and only briefly touched upon in the results was that all participants during all conditions correctly identified the symbol and quadrant of the symbol. A previous study conducted by Lin and Hsu obtained opposite results where an auditory cue increased the percentage of task error.[134] The task incorporated into their study was significantly more complicated and included multiple levels of increasing difficulty. It is conceivable that our task was simply too easy. Future studies incorporating a more difficult task is warranted.

For the second task, there were no significant differences found for course completion time or number of deviations between groups. What is interesting is the without distraction group showed longer circuit completion times and a higher number of course deviations. The post-hoc tests revealed this to be an order effect with significant improvement across measurements between the first and second trials. We believe this to be a flaw in the design of the experiment. Subjects were provided only one trial run before testing commenced. Therefore, it is conceivable that the downward trend of measurements was a learning effect. Hence, any future studies should incorporate multiple training sessions to achieve a baseline before the distraction variable is introduced.

Study limitations include the previously mentioned statistical power and flawed training protocol. Another limitation to the study could be response bias in the form of subject fatigue. Though the results do not necessarily indicate this as a confounding factor, this protocol was administered alongside another study protocol which required back to back visual measurements. It would be prudent to rerun the protocol by itself to determine if response bias influenced the outcome. Therefore, future research should incorporate an increased number of subjects, more extensive training on tasks in addition to carefully timing administration of the protocol.

Additional areas of research that may prove intriguing is the incorporation of electroretinograms (ERGs) and visual evoked potentials (VEPs). Research focusing on event-related potentials (ERPs) has shown a 50% suppression indicating a significant degradation on object and event identification while driving.[125] It is possible degraded ERPs are linked to degraded visual acuity and contrast sensitivity. Therefore, it would be fruitful to understand if a correlation exists between visual acuity, contrast sensitivity and suppressed ERGs and VEPs under driving distraction conditions.

Our results suggest that a driver traveling 65 miles/hour (95.33 feet/sec.) attending to an automobile display for 0.24 sec. would experience diminished driving visibility for 22.88 feet (1.6 car lengths), posing a formidable threat to safety. This effect is likely exacerbated in elderly individuals, given their substantive loss of useful field-of-view, which is the ability to identify centrally viewed targets while detecting peripheral targets.[142] Future research, involving older individuals and those with ocular, systemic and/or neurologic disease, may reveal more deleterious effects of visual and auditory distraction on response time and visual performance in critical tasks like driving.

In conclusion, the study expanded the literature by incorporating visual acuity and

contrast sensitivity measures. Past research has mainly focused on response/reaction time, visual scanning, eye movements, and ERPs.[121,143,144] Our study found contrast sensitivity for L cones was significantly impacted. Future research should incorporate expanded training protocol, increased power, ERGs and VEPs.

Discussion

The present dissertation focused on vision within the context of visually demanding occupations and how vision tests can be utilized for occupational screening. The Commission on Behavioral and Social Sciences outlined considerations when selecting a test for occupational purposes considerations.[41] First, clinical tests are not set up to establish a minimum required score for job entry. Study #1 compared and contrasted three different computerized color vision tests for contrast sensitivity and analyzed how the minimum cutoff score differed between the tests. All systems showed 100% sensitivity for detecting and identifying type of CVD and high specificity for confirming CVN. The log CS values provided by each test are similar with the exception of the 55 score on the Konan CCT-HD® which equates to log CS of 1.45. Furthermore, the displays used by each test yields slightly different targeted values. For instance, the Konan CCT-HD® system yielded higher values for L and M cone CS, attributable to its finer gradation in contrast steps and PSI method of achieving a threshold while the Innova CCT with extended contrast range yielded higher short wavelength cone scores due to the larger character size. Additional studies assessing how the cutoff score equates to operational performance is recommended.

Second, practical field tests may be more suitable than a clinical color vision tests since they ideally replicates tasks required on the job. Study #2 assessed NSLT. The signal light stimulus is an exact replica of what is utilized on the railway system and the test itself is

administered at the exact distance a railway employee is expected to correctly identify the color of a wayside signal. Requirements for color vision within the railway industry have been well documented. While the Lagerlunda incident may or may not be due to a color vision deficiency, the incident sparked a movement for railway employees to be color vision tested.[39,145] To assess railway employees color vision, various iterations of the lantern test have been developed with each prototype showing some technological progression.[72] Most of the lantern tests developed did not focus on replicating real world conditions on the railway.[42,43] Study 2 demonstrated that a test may have suitable sensitivity and specificity but when screening protocols are not followed, as was the case in Goodwell OK, accidents occur that are financially costly and fatal in nature. From this aspect rigorous testing protocols are critical to protect the company and the surrounding community from tragedy. Our results showed that protocol administration makes a marked difference in the sensitivity and specificity of the NSLT. In fact, sensitivity increased 14% by implementing a four different colored light demonstration versus the two same-colored light demonstration. Ultimately, this change in procedures resulted in 100% sensitivity and specificity. While the test has demonstrated replication of tasks required on the job, further studies increasing the number of CVDs is warranted.

Third, accessibility of clinical tests may be an issue since not all clinics carry the same tests. Substitute or replacement tests could be beneficial where the standard test is not available. The FM-100 test is often used for vocational purposes where hue discrimination is of the upmost importance, such as in the field of jewelry appraisals where small errors in hue discrimination can lead to significant differences in gemstone valuation. However, not all clinics will have the FM-100. Study #3 determined if the Innova CCT could predict performance on the FM-100 thereby providing a potential alternative test to the FM-100 Hue for initial and periodic screening

of jewelry appraisers as required by the NAJA. Results indicate the Innova CCT may be an effective substitute for the FM-100 to provide certification of jewelry appraisers, but the small sample size warrants additional comparative validation to support sole utilization of the Innova CCT, and the Innova CCT and FM-100 are distinct color vision tasks. NAJA may consider using CCT results in locations where the FM-100 is unavailable and applying our derived passing score of 60 or above to achieve certification. A surprise finding was lower than age-matched norm TES scores in jewelry appraisers despite mitigating senescence factors. The current perspective on the FM-100 Hue is that lower TES scores are due to a practice effect.[103,106] It is conceivable that the enhanced jewelry appraiser's hue discrimination reflects perceptual learning, wherein reward-based repetition on specific tasks can improve performance even in adulthood beyond so-called critical periods.

Fourth, clinical tests are not designed to reflect the complex work environment. Study #4 expanded previous research on cell phone distraction to auditory distraction with a navigational system. Delayed response time with visual distraction is comparable to verbal distraction during hands-free phone calls. If a vehicle is traveling 65 miles/hour (95.33 feet/sec.), then a visual distraction for 0.24 sec. would diminish direct visibility for 22.88 feet (1.6 car lengths), large enough to render low contrast targets undetectable, posing a formidable threat to safety.

Limitations

A limitation was potential subject fatigue. Visual fatigue has been found to impact assessment.[93,146] There were multiple tests run back-to-back which could have impacted one or multiple test results. While fatigue is known to impact vision, it would be prudent to understand the interaction of test order and fatigue especially when investigating the efficacy of multi-test protocols utilized in occupational testing.[64] Furthermore, it is plausible that utilizing a multi-test

protocol can induce a learning effect. For example, in the visual distraction study, the L cone contrast sensitivity measure was always displayed first. It is also the only statistically significant effect across chromatic sensitivity measures. Therefore, there could have been a learning effect to the M and S cones. This learning effect was also found in the Mario cart results revealing thata certain level of task training to baseline must occur before the dependent variable is measured.

Learning effects were also a limitation of the visual distraction and jewelry appraiser studies. The excellent hue discrimination found in the small cohort of jewelry appraisers could be perceptual learning or a known learning effect of the FM-100 Hue. While increasing the subject pool and rerunning the study is one way to investigate this, adding a control group on non-NAJA older individuals could help determine if jewelry appraisers do have better then age-matched norms for hue discrimination. Additional measures such as ERGs and VEPs could reveal a difference between jewelry appraisers and an age-matched control group.

Future Studies

Several lines of research have been identified as a result of the studies conducted for this dissertation. When assessing a newly developed signal light/lantern test for occupational purposes, establishing the sensitivity and specificity is a first step towards determining reliability and validity of the test. Additional factors requiring investigation are administrative procedures such as repeat runs, test distance, and blur. The current study highlighted the importance of administration procedures. However, we only tested a small subset on repeat trials. Previous research has noted the importance of repeat runs on a lantern test to decrease the chance pass rate of CVDs.[82] Repeat testing applies more stringent passing criteria but should be assessed at the actual distance in which employees are required to identify signal coclors.[83] Along a similar vein, it would be prudent to determine if a single test protocol is effective for screening applicants or if

a multi-test protocol is warranted to ensure only individuals with normal color vision are put into safety critical jobs.[84,85] Studies have found that clinical vision tests are predictive of lantern outcomes and it is plausible that incorporating clinical tests as part of the screening protocol would provide a more holistic measure of visual function. Another line of research in regards to the signal light centers on blur. Railway workers are required to identify colors under poor visibility. The current study found no effect but the level of blur was fairly innocuous. Future studies significantly reducing VA are warranted. As expected, testing distance made a significant impact on pass rates which is in line with previous research.[88,89] Decreasing distance increases the chances of CVDs passing the occupational test. The current study tested only CVNs at shorter distances. Future studies should include CVDs. The current study analyzed the predictive capabilities the Innova CCT. Past research has in this area has been conflicted.[48,90,147] The current regression analysis revealed that the abnormal Innova CCT 100-point score was predictive of the railway outcome and the abnormal Innova CCT log CS was predictive but only at an alpha of 10. A future study with a larger cohort of CVNs and CVDs is warranted.

Regarding the computerized color vision tests, the current study showed all systems were adept for detection and diagnosis. The most important next step is to determine if passing scores set by military organizations are operationally suitable. It may be prudent to determine if single or multi-test clinical protocols in addition to an operationally based vision assessment is warranted for certain occupations.

The use of clinical tests, albeit as a suitable replacement, was explored in the jewelry appraiser study. Our results showed that the Innova CCT may be a suitable replacement however additional research is warranted. The research should include a larger cohort of jewelry appraisers and incorporate additional computerized color vision tests. The predictive nature of

the Innova CCT was confined to M and S wavelength cones. It would be interesting to see if this holds true for other computerized color vision tests. As previously stated, the excellent hue discrimination of jewelry appraisers could be a practice effect, a well-known factor of the FM-100. However, it could be due to perceptual learning. In order to test this theory, research including control measures, VA measures, and additional demographic information such as years working in the field are required. Furthermore, it would be interesting to conduct a study utilizing ERG/VEP in a study assessing subjects with excellent color discrimination against those with average color discrimination.

A study incorporating ERG and VEPs to assess the effects of visual and auditory distraction would interesting as well. Prior research on ERPs has shown a 50% suppression on object and event identification while driving.[140] It would be important to determine how distraction impacts different stages of the visual pathway. Additional studies into distraction would require protocol refinement to include implementing training to baseline and randomizing cone contrast sensitivity measurements. Increasing the difficulty level of the distraction task is necessary as well.

Conclusions

In summary, this body of work addressed several aspects of occupational visual testing. The first study demonstrated the importance of correct test administration leading to a 100% sensitivity and specificity for the signal light. The Konan CCT-HD®, NCI, and Innova CCT were found to have 100% sensitivity for detection and identification of type of CVD and high specificity for confirming CVN. The Innova CCT was found to be predictive of both the railway signal light test and the FM-100. An unexpected finding was lower than age-matched norm TES scores in jewelry appraisers despite mitigating senescence factors. Last, delayed response time

with visual distraction is comparable to verbal distraction during hands-free phone calls rendering low contrast targets undetectable, posing a formidable threat to safety.

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Appendices

Appendix A: IRB Approval I

UNIVERSITY OF THE INCARNATE WORD

December 5, 2018

To: Dr. Jeffrey Rabin

From: University of the Incarnate Word Institutional Review Board, FWA00009201

Jeffrey:

Your request to conduct the study titled 'Validation of the Union Pacific Light-Canon Color Vision Field Test' was approved by review on 12/05/2018. Your IRB approval number is 18-12-001. You have approval to conduct this study through 12/5/2019.

Please keep in mind the following responsibilities of the Principal Investigator:

1. Conducting the study only according to the protocol approved by the IRB.
2. Submitting any changes to the protocol and/or consent documents to the IRB for review and approval prior to the implementation of the changes. Use the **IRB Amendment Request** form.
3. Ensuring that only persons formally approved by the IRB enroll subjects.
4. Reporting immediately to the IRB any severe adverse reaction or serious problem, whether anticipated or unanticipated.
5. Reporting immediately to the IRB the death of a subject, regardless of the cause.
6. Reporting promptly to the IRB any significant findings that become known in the course of the research that might affect the willingness of the subjects to participate in the study or, once enrolled, to continue to take part.
7. Timely submission of an annual status report (for exempt studies) or a request for continuing review (for expedited and full Board studies). Use either the **IRB Study Status Update** or **IRB Continuing Review Request** form.
8. Completion and maintenance of an active (non-expired) CITI human subjects training certificate.
9. Timely notification of a project's completion. Use the **IRB Closure** form.

Approval may be suspended or terminated if there is evidence of a) noncompliance with federal regulations or university policy or b) any aberration from the current, approved protocol.

If you need any assistance, please contact the UIW IRB representative for your college/school or the Office of Research Development.

Sincerely,

Mary Jo Bilicek
Research Compliance Coordinator
University of the Incarnate Word
(210) 805-3565
bilicek@uiwtx.
edu

Appendix B: IRB Approval II

UNIVERSITY OF THE INCARNATE WORD

June 13, 2019

To: Dr. Jeffrey Rabin

From: University of the Incarnate Word Institutional Review Board, FWA00009201

Jeffrey:

Your request to conduct the study titled The Impact of Visual Distraction on Target Detection and Simulated Driving Performance was approved by expedited review on 06/13/2019. Your IRB approval number is 19-06-004. You have approval to conduct this study through 6/13/2020.

The stamped informed consent document is uploaded to the Correspondence section in the Research Ethics Review system. Please use only the stamped version of the informed consent document.

Please keep in mind the following responsibilities of the Principal Investigator:

1. Conducting the study only according to the protocol approved by the IRB.
2. Submitting any changes to the protocol and/or consent documents to the IRB for review and approval prior to the implementation of the changes. Use the **IRB Amendment Request** form.
3. Ensuring that only persons formally approved by the IRB enroll subjects.
4. Reporting immediately to the IRB any severe adverse reaction or serious problem, whether anticipated or unanticipated.
5. Reporting immediately to the IRB the death of a subject, regardless of the cause.
6. Reporting promptly to the IRB any significant findings that become known in the course of the research that might affect the willingness of the subjects to participate in the study or, once enrolled, to continue to take part.
7. Timely submission of an annual status report (for exempt studies) or a request for continuing review (for expedited and full Board studies). Use either the **IRB Study Status Update** or **IRB Continuing Review Request** form.
8. Completion and maintenance of an active (non-expired) CITI human subjects training certificate.
9. Timely notification of a project's completion. Use the **IRB Closure** form.

Approval may be suspended or terminated if there is evidence of a) noncompliance with federal regulations or university policy or b) any aberration from the current, approved protocol.

If you need any assistance, please contact the UIW IRB representative for your college/school or the Office of Research

Development. Sincerely,

Mary Jo Bilicek
Research
Compliance
Coordinator
University of
the Incarnate
Word (210)
805-3565
bilicek@uiwtx.edu

Appendix C: IRB Approval III

UNIVERSITY OF THE INCARNATE WORD

July 31, 2019

To: Dr. Jeffrey Rabin

From: University of the Incarnate Word Institutional Review Board, FWA00009201

Jeffrey:

Your request to conduct the study titled Evaluation of Color Vision Testing for Jewelry Appraisers was approved by expedited review on 07/31/2019. Your IRB approval number is 19-07-008. You have approval to conduct this study through 7/31/2020.

The stamped informed consent document is uploaded to the Correspondence section in the Research Ethics Review system. Please use only the stamped version of the informed consent document.

Please keep in mind the following responsibilities of the Principal Investigator:

1. Conducting the study only according to the protocol approved by the IRB.
2. Submitting any changes to the protocol and/or consent documents to the IRB for review and approval prior to the implementation of the changes. Use the **IRB Amendment Request** form.
3. Ensuring that only persons formally approved by the IRB enroll subjects.
4. Reporting immediately to the IRB any severe adverse reaction or serious problem, whether anticipated or unanticipated.
5. Reporting immediately to the IRB the death of a subject, regardless of the cause.
6. Reporting promptly to the IRB any significant findings that become known in the course of the research that might affect the willingness of the subjects to participate in the study or, once enrolled, to continue to take part.
7. Timely submission of an annual status report (for exempt studies) or a request for continuing review (for expedited and full Board studies). Use either the **IRB Study Status Update** or **IRB Continuing Review Request** form.
8. Completion and maintenance of an active (non-expired) CITI human subjects training certificate.
9. Timely notification of a project's completion. Use the **IRB Closure** form.

Approval may be suspended or terminated if there is evidence of a) noncompliance with federal regulations or university policy or b) any aberration from the current, approved protocol.

If you need any assistance, please contact the UIW IRB representative for your college/school or the Office of Research

Development. Sincerely,

Mary Jo Bilicek
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