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Presentation Outline

- Introduction
- Color Vision Basics
- Color Vision Standards
  - Developing a “Standard”
- Color Vision Testing
  - What’s new out there

Color Vision Basics

- Human color perception is a complex topic

Color Stimulus (Science)
- Spectral characteristics of light entering
  - Eye and brain
  
VS

Color Perception (Psychophysical)
- Subjective experience of that stimulus
  - Functional, judgment, learned, emotional

Color Vision Basics

Human eye has 3 different cones:

Chromosome Channel
- X
  1. Red (Peak: 564 nm)  
  - Twice the number of green
  2. Green (Peak: 534 nm)
- 7
  3. Blue (Peak: 420 nm)  
  - Least number
  - Different distribution

Color Vision Basics

To see all potential colors, you must have:

1. Normal R / G Channel
2. Normal B / Y Channel
Understanding Color Vision Deficiencies

Color Vision Basics
- Depends on three normal cone types (red, green, and blue)

Color discrimination depends on the difference in cone stimulation

Color Vision Basics
- Hereditary color deficiency
  - 8-10% males
  - 0.5% females
- Acquired color deficiency
  - 5-15% general population

Color Vision Basics
- Lack of red cones
  - Protan Dichromat (Congenital)

Lack of red cones in Protan Dichromat (Congenital)
Color Vision Basics
• Or green cones

441nm 566nm
B G R
1% of Males

Deutan Dichromat (Congenital)

Color Vision Basics
• Or sensitivity shift (an anomaly)

441nm 541nm
B G R
1% of Males

Protanomalous (red shifted toward green)

Color Vision Basics
• Or green toward red

441nm 566nm
B G R
5% of Males

Deuteranomalous (green shifted toward red)

Color discrimination depends on difference in cone stimulation

Small difference

B G R

Small difference

← Look the same!

Color Vision Terminology (Congenital Incidences)

Normal trichromat (Color Normal)
• 92% Males
• 99.5% Females (It's a man's disease!)

Anomalous trichromat (Color Weak)
• Red/Green: (At birth: 6-8% Males; 0.5% Females)
  ◦ 5-6% Green weak (deuteranomalous)
  ◦ 1% Red weak (protanomalous)
• Blue/Yellow: (At birth: 0.005% Males; 0% Females)

Dichromat (Color Blind)
• Red/Green:
  ◦ 1% Green blind (deuteranope)
  ◦ 1% Red blind (protanope)
• Blue/Yellow:
  ◦ 0.005% (tritanope)

Achromat (Rare)
• No cones, no Color, no vision
Color Vision Terminology

- **Deutans and Protans**
  - General non-specific terms that refer to type of cone involved
  - Includes all degrees of anomalous trichromats and dichromats

Seeing “Yellow”

- **Nagel Anomaloscope**
  - (Rayleigh Equation)
  - Nagel Anomaloscope (Rayleigh Equation)
  - (589 nm Metamer Match of red and green)

*Types of Color Vision Deficiencies*

- **Congenital (Sex-linked)**
  - 8-10% Males, 0.5% Females
  - Almost exclusively Red/Green

- **Acquired** (Ocular disease until proven otherwise)
  - Ocular diseases (e.g. glaucoma, diabetes)
  - Meds/Drugs (e.g. Chloroquine, BCP, Viagra, antibiotics)
  - Phototoxicity (sunlight, lasers)
  - Usually Blue/Yellow, but can be Red/Green
  - 5-15% of general population, equal opportunity

- **Induced**
  - Colored filters and lenses
  - (HCV, LEP, windscreens, blue-blockers)

*Acquired Color Vision Deficiencies*

- Affects 5 - 15% of population
- Equally affects both sexes
- Typically Blue / Yellow defect, but can be both
- Associated with aging, diseases, medications and drugs (over 200 diseases / 300 meds)
- May be insidious and precede any other visual loss
Acquired Color Vision Deficits

- Common Drugs
  - Oral Contraceptives
  - Oral Diabetic Agents
  - Antibiotics (Tetracyclines)
  - Antimalarials (Chloroquine, Quinine)
  - Digoxin And Digitalis
  - Antituberculostatics (INH, Ethambutol)
  - Ethanol
  - Tobacco
  - Nitroglycerin
  - Viagra
  - Diuretics (Thiazides)

Color Vision Deficiencies

- Acquired vs. Congenital
  - Clinical distinctions
    - Recent color naming problems
    - Asymmetric involvement
    - May be monocular
    - Usually Blue / Yellow
    - Equally affects females
    - Defect may change
    - Other associated ocular pathology
    - No pattern

Spectral Sensitivity (Least Detectable Hue Change)
Individual Plot

Color Vision Basics

While dichromats perform similarly, each anomalous trichromat is different and cannot be compared... except in broad terms.

Sildenafil Citrate (V)

- Summary of effects
  - Literature is scant, little published
  - Blue-green tinge (cyanopsia)
  - 3% report visual effects at 50 mg
  - 10% report visual effects at 100 mg
  - 40-50% report visual effects at 200 mg
  - 37.5% had significant error scores on FM 100
  - Effects last 1-6 hours, possibly longer
  - Reversible... So far

Induced Color Vision Deficits

Physical Characteristics and Perceptual Effects of “Blue-Blocking” Lenses

- Color Vision
  - Normals and anomalous subjects
    - Induced severe tritan defect in all
    - Increased mean total error score (24 - 204); decreased hue discrimination
      - Worsened under decreased illumination
  - Dichromats
    - Total random distribution
    - Hue discrimination non-existent

Origin of Occupational Color Vision Standards

“The Short Story”
What’s changed?

- Technology for sure
  - Hand-waving to candles, flags to assorted signal lights and full spectral multi-color displays (EFIS)
  - From incandescent to CRTs, fluorescents, LEDs and laser projectors of all types
    - All different, continuously growing
    - Rely on color for speed of information transfer
- Mixed gender operators
- Waiverable diseases/medications expanded
  - Over 200 diseases / 300 medications can induce CV deficits
- There are distractions and new hazards everywhere

What’s changed?

- New operational phototoxic hazards (lasers)
- Color vision cheating scams
- Infrequent and improper CV field testing
  - Need guidance on how to beat a CV test?
    - Google it!
- We use or require an array of protective ensembles and protective lenses and filters
- Changing regulations, government oversight

Multi-Function Vision Testers
(Color Vision Test)

Electronic Multicolor Displays

Electronic Multicolor Displays
(Overall Literature)

- If designed properly, EFIS color displays optimize and maximize information transfer
  - Increases accuracy
  - Reduce visual search times

Electronic Multicolor Displays
(Overall Literature)

- Designed for color normals
- Fail to incorporate
  - Defective color vision
  - Selective wave-band filter effects
    - Laser eye protection
    - Colored lenses and visors
Sunglasses and Filters

- **Blue-blocking lenses** (yellow-orange)
  - Block UVs and short visible wavelengths (violet-blue)
  - Protects retina (macula) from phototoxic effects
  - Induce significant tritan (B/Y) CV defect
  - Exacerbates existing CV defects
    - Worsens with decreasing illumination
  - Render some monochromatic

- **Polarizing lenses**
  - Reduce reflected glare
  - Cross-polarization effects induce blind spots and color and distortion

Developing a Color Vision Standard

Color Vision Testing Strategy

- **Based on valid job task analysis**
  - Identify all pertinent CV tasks involved
    - Identify all critical CV tasks, frequency, performance expectations, and consequence of failure
      - Position descriptions
      - Interviews
      - Field observations
    - Assess CV tasks for relevance, available redundancies, expected responses
    - Embrace all potential environments and conditions

- **Goal**
  - Identify mission critical and safety related CV tasks
    - Find just one, you have your standard

Color Vision Testing Strategy

- **Assess existing CV testing strategy**
  - Tests utilized
    - Determine if it gets you there
  - Frequency of testing
  - Consider selection and retention issues
  - Examine testing environments
  - Need for central review and/or validation processes
  - Option of a practical field test
  - Performance expectations
    - Consequences of failure
  - Management of change over time

Color Vision Testing Strategy

- **Testing should...**
  - Be reliable, easy to administer ("idiot-proof")
  - Determine type and degree of defect
  - Be resistant to scamming or compromise

- **Employ central oversight and validation processes**

- **Include all functional aspects of CV defectives**

- **Embrace performance limitations and expectations**

Performance Limitations

- **(Color Vision Defectives)**
  - Reduced visual range
  - Slower reaction times (0.4-0.5 secs)
  - Increased processing errors
  - Higher thresholds (reduced performance)
    - Under reduced illumination
    - Hypoxia
Color Vision Testing Strategy

- Addresses performance expectations
  - Risk management/consequence of failure
    - National security
    - Personal and public safety
    - Resources
    - Business impact
    - Legal consequences

- Field validation

NATO WG-24 (2001)
Color Vision Testing Recommendations

- Monocular testing
- Under proper illumination
- Should include red / green and blue / yellow testing (congenital and acquired deficits)
  - PIPs for screening
  - Anomaloscopes for diagnosis
- No lanterns (nein, nada, nyet, non, iie...!)
- Should be annual or repeated in keeping with national flying exam practices
- Strive for international uniformity

Color Vision Testing Options
(Assumes critical CV tasks involved)

- Test for normal CV in everyone
  - Optimizes performance under all potential scenarios
  - Best that anyone can do

- Accept some CV defectives
  - Develop acceptable “color-safe” category
    - Complicated
      - Requires validation studies under variable conditions

- Ignore CV testing altogether

“A color defective who, for reasons of his own, hides his defect might do well, but a color defective who insists that he ‘knows all colors,’ that he is ‘perfectly o.k.’ is a menace. Of course, he sees all colors in his own way and in his own way ‘knows all colors’ – all his colors. But he must realize that he sees them not the way the rest of us see them, that we are in the majority and that tests, traffic lights, neckties, decorating schemes, wire codes were made to serve us, not him.”

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( Assumes critical CV tasks involved )

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Early Occupational CV Testing
(Post 1875)

- Focused on:
  - Males (male dominated professions)
  - Congenital red/green CV deficiencies
  - Red and green signal light and navigational aid recognition
  - Mass screening strategies in young healthy occupational applicants
    - Assumed CV deficiency would remain stable
    - Individuals would not cheat
  - Resultant strategy:
    - Congenital red/green PIP screening followed by practical CV lantern test

WWI Aviation CV Standards

- Color Vision ( in the A.E.F. )
  - “We consider that (color vision) is most important for the aviator to be able to recognize colors rapidly in a reduced light and in a fog.”

- Wilmer and Berens
  ( Aviation Medicine in the A.E.F.)
**WWI Aviation CV Standards**

- **Color Vision (in the A.E.F.)**
  
  "...proper recognition of colors plays an important part in success of all types of fliers."
  
  - On maps: green woods, blue rivers, yellow roads, black railroads, and brown towns
  - Skyrockets are: white, red or green
  - Bengal flares are: red and white
  - Aerodromes: red, green or white lights
  - Aeroplanes: red light on port, green on starboard
  - In a dogfight:
    - Experienced aviators argued that it was a necessity "...to recognize colors on a machine to avoid the possibility of shooting down a friend."

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**Early Occupational CV Testing (Post 1875)**

- **Hue Discrimination**
  
  - Seebeck (1837)
    - 200-300 Pieces of paper, glass, and wool
  - Holmgren Wool Test (1877)
    - Jennings Self-Recording Color Test (1896)
      - Perforated cardboard with red/green confusion colors

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**Early Occupational CV Testing (Post 1875)**

- **Pseudoisochromatic Plate (PIP) Tests**
  
  - Stilling Plates (1877)
    - Based on confusion colors of a red-green CV defective "maler" and a blue-yellow CV defective teacher
  - Ishihara Plates (1917)

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**Early Occupational CV Testing (Post 1875)**

- **Practical Tests**
  
  - Lantern Tests
    - Williams (1892)
    - Eldridge-Green (1891)
  - Anomaloscope
    - Nagel (1907)

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**Early Occupational CV Testing (Post 1875)**

- **Problems emerged before, during, and after WWII**
  
  - Stilling and Ishihara PIP tests “alien property”
    - German and Japanese inks unavailable
    - Initially, "bootleggers" reproduced (stole) original PIP plates
  - Later, the “gold rush” for a better PIP test ensued
    - Armed Forces National Research Council
      - US Army School of Aviation Medicine
      - US Navy’s Submarine Medical Research Laboratory
      - PIP scoring manipulations reduced effectiveness
  - Test administration in the field unreliable
    - Lighting and timing issues
  - Poor correlation of practical tests (lanterns) with actual job tasks, e.g. for flying
  - Cheating

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"It was the peculiar situation American ophthalmology met during the War years which made our scientists look for screening tests with passing scores...which...forced them to degrade essentially diagnostic tests like the Stilling and the Ishihara into serving this purpose."

Arthur Linksz, MD

“An Essay on Color Vision”
**WWII CV Testing Strategy**

- Testing strategy during and after WWII
  - Initial screening with PIP test
    - Ishihara, Dvorine, American Optical (AO), etc
  - Secondary testing with occupational lanterns

**Color Vision Tests and Testing Strategies**

**Color Vision Testing Realities**

- Many practitioners do not understand CV and CV testing well
  - Including most ophthalmologists
- Most common CV tests designed for screening only
  - Anomaloscope is “Gold Standard”
- No CV test is perfect, but only a few:
  - Determine type and degree of CV defect
  - Difficult to scam

**Color Vision Testing Pitfalls**

- Invalid illuminant

**Color Vision Testing Pitfalls**

- Invalid illuminant
- Contaminated test environment
Color Vision Testing Pitfalls
- Invalid illuminant
- Contaminated test environment
  - Need darkened room without windows

Color Vision Testing Pitfalls
- Invalid illuminant
- Contaminated test environment
- Binocular testing
  - Acquired disease presents asymmetrically
  - Does not always impact visual acuity first
    - Glaucoma
    - Diabetes

Color Vision Testing Pitfalls
- Invalid illuminant
- Contaminated test environment
- Binocular testing
- Improper test distance
  - See test instructions

Color Vision Testing Pitfalls
- Invalid illuminant
- Contaminated test environment
- Binocular testing
- Improper test distance
  - Ignore timing requirements

Color Vision Testing Pitfalls
- Invalid illuminant
- Contaminated test environment
- Binocular testing
- Improper test distance
  - Ignore timing requirements
  - Improper test selection

Color Vision Testing Pitfalls
- Invalid illuminant
- Contaminated test environment
- Binocular testing
- Improper test distance
  - Ignore timing requirements
  - Improper test selection
Color Vision Testing Pitfalls

- Invalid illuminant
- Contaminated test environment
- Binocular testing
- Improper test distance
- Ignore timing requirements
- Ineffective test choice
  - Wrong test, bad test
  - Should test for congenital and acquired etiologies

Color Vision Testing Pitfalls

- Incorrect illumination
- Light contamination
- Binocular testing
- Ignoring time limits
- Improper test distance
- Improper test selection
- Repeating test
- Improper test angle
- Improper test selection
- Response hints
  - Sighs, wiggles, gasps, winks, boos, cheers, etc
- Cheating schemes
  - Test studying, chat rooms
- Allowing test handling
- Faded, stained test

Color Vision Testing Realities

- Practical CV tests are problematic
  - Require task validation
  - Do not embrace environmental dynamics
  - Lag behind technology developments
- CV performance can change with...
  - Level and type of illumination
  - Atmospheric conditions
    - Fog, smoke, rain, haze, dust, hypoxia, etc
  - Type and size of targets
  - Diseases, medications, drugs, lenses

Pseudoisochromatic Plates (PIPs)

- Ishihara (multiple editions)
- Dvorine (2nd edition)
- AO (multiple editions)
- Igaku-Shoin (SPP1, SPP2, SPP3)
- Hardy-Rand-Rittler (HRR 4th edition)
- Farnsworth F2
- Stilling-Velhagen
- Tokyo Medical College
- Many others

Standardized Illumination (Illuminant C)

- MacBeth Easel Lamp
- True Daylight Illuminator

Color Vision Basics

- Color perception changes with type and level of illumination

CV RAF 2009
Pseudoisochromatic Plates (PIP)

- Most common color vision test “screener”
- Sensitive, rapid
- Detection of hereditary color deficiency (90-95% accurate)
- Colored plates arranged into a booklet. Figure and background appear the same to color deficient patient
- Pip 1 detects red-green deficiency, but does not determine type or severity
- Pip 2 and 3 detect red-green and blue-yellow acquired deficiencies

“A person with abnormal color vision cannot be educated to see colors normally. He possibly can be educated to do better in a mechanized color-screening test.”

Arthur Linksz, MD
“An Essay on Color Vision”


- Applicants
  - Screened in field by Pip 1
    - Ishihara, Dvorine, or original AO PIPs (PIP Is)
    - No Richmond or Beck Engraving editions allowed
  - If pass Pip 1, applicant goes to Medical Flight Screening (MFS)
    - Pip 1 (R/G: congenital)
    - SPP 2 (B/Y: some R/G: acquired)
    - SPP 3 (R/G + B/Y: mixture)
    - F2 (R/G + B/Y)

Arthur Linksz, MD
“An Essay on Color Vision”
**Hue Discrimination Tests**

- **Farnsworth-Munsell 100 Hue Test (FM 100)**
  - 85 iso-illuminant, equal chroma caps
  - Quantitative scoring
  - Ineffective CV screener
    - Time consuming
    - Misses severe anomalous trichromats
  - Reliably identifies dichromats
  - Good for baseline comparisons

- **Farnsworth Dichotomous Test (Panel D15)**
  - 15 iso-illuminant, equal chroma caps
  - Designed for wire identification tasks
  - Ineffective CV screener
    - Misses severe anomalous trichromats
    - Reliably identifies dichromats

- **Lanthony Desaturated 15 Hue Test**
  - More sensitive version for acquired defects

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**Anomaloscopes**

*(The International “Gold” Standard)*

- Based on metameric matches
  - Rayleigh equation: 589 nm (545 + 670)
  - Moreland: 480 nm (440 + 500)
- Identify type and degree of deficiency
- Other CV tests are validated against (K)
- Difficult to scam

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**Nagel Anomaloscope Scoring**

*(Rayleigh Equation)*

\[
\begin{array}{c}
\text{Normal Trichromats} \\
\text{Anomalous Trichromats} \\
\text{Dichromats}
\end{array}
\]

**Moreland Anomaloscope**

*(Moreland Equation)*

- 440 nm
- 545 nm

**FARNSWORTH Lantern**

*(FALANT)*

- Developed for WWII US Navy signalmen
  - Designed to pass “mild” CV defectives
  - Adopted as Navy aviation screener in 1954
- Dropped by USAF in 1993
  - Misclassifies CV defectives
    - Misses significant defects
    - At heart of 2002 FedEx mishap
- 140 CV defective pilot applicants
- Definitive diagnosis by anomaloscope
- 50% passed the FALANT, to include...
  - 3/5 (60%) moderate protanomalous
  - 12/23 (52%) severe protanomalous
  - 13/18 (72%) moderate deuteranomalous
  - 24/46 (52%) severe deuteranomalous

Color Vision Lantern Tests (Just a Sampling)
- Edridge-Green (1891)
- Williams (1892)
- Thomson (1892)
- Board of Trade (BOT) (1895, 1938, 1943)
- Beyne/Tritest L3 (1925)
- Martin (1939, 1943)
- Giles-Archer (1940)
- USAFSAM Color Threshold Test (CTT) (1943)
- Royal Canadian Navy (RCN) (1943)
- Farnsworth (FALANT) (1946)
- Spectrolux (1985)
- Optec 900 (FALANT) (1992)
- CN Lantern (CNLAN) (1999)
- RailCorp Lantern (RL)
- Biscuit gun
- Signal light gun tests

Color Vision Related Mishaps
- Major transport accidents in 1875
  - Train collision near Lagerlunda, Sweden
    - Outcry for CV testing and standards
  - Ship collision off US coast
- WWII
  - Officer shot by student who failed to identify colored signal
  - Bomber shot down when pilot failed to respond to color signal
  - Color vision defective brothers involved in two aircraft mishaps attributed to color
  - Lost US Navy submarine? (Christmas tree lights)

NTSB (1996): Acquired CV defect that prevented correct ID of wayside track signals
- Missed by examiner

NTSB (2012): Acquired CV defect
- Misidentified wayside signals
- Also missed by examiner
FedEx 727 Mishap

26 July 2002
Tallahassee, Florida
(NTSB Report: AAR-04/02)

FedEx 727 Mishap

26 July 2002
Tallahassee, Florida
(NTSB Report: AAR-04/02)

PAPI: A Pilot's eye view

• NTSB Aircraft Accident Report AAR – 04/02
(FedEx Flight 1478, Tallahassee, Florida, 26 July 2002)

♦ Probable cause
  • Captain’s and First Officer’s (FO) failure to establish
    and maintain proper glidepath during the night visual
    approach to landing

♦ Contributing to the accident
  • Captain and FO fatigue
  • Captain and FO failure to adhere to company flight
    procedures and to monitor the approach
  • FO’s color vision deficiency

• NTSB Aircraft Accident Report AAR – 04/02
(FedEx Flight 1478, Tallahassee, Florida, 26 July 2002)

♦ Conclusions (selected)
  • NTSB concluded that “1 or more tests used in aviation
    (e.g., The Farnsworth Lantern) are not adequate; these
    tests should be identified and their use discontinued.”
  • “Existing FAA color vision tests may not ensure
    detection of color vision deficiencies that can be
    detrimental to safety...”
  • “FO’s severe color vision deficiency made it difficult for
    him to correctly identify the color of the PAPI system.”

• NTSB Aircraft Accident Report AAR – 04/02
(FedEx Flight 1478, Tallahassee, Florida, 26 July 2002)

♦ Recommendations to FAA
  • Conduct research to determine effectiveness of current
    FAA color vision test protocols (including color signal
    light test)
    ▪ Including time requirements to perform each task,
      particularly under emergency and hypoxic conditions (A-
      04-46)
    ▪ Develop a standard battery of tests (A-04-47)

“Color Vision Testing by Farnsworth
Lantern and Ability to Identify Approach
– Path Signal Colors”
BL Cole and JD Maddocks
(ASEM, Jun 2008)

♦ Passing FALANT does not ensure CVD pilots
  can distinguish PAPI signal colors
♦ Scoring criteria for FALANT too lenient
♦ Recommended changes to PAPI signal lights

CV RAF 2009
New CV Testing Strategies and Technologies

- Cone contrast
- Spatial-temporal luminance
- Pseudoisochromatic computer generation

Cone Contrast Test (CCT)

- Devised by Dr. Jeff Rabin
- Refined at USAFSAM
- Tests individual cone contrast sensitivities against neutral background
- Computer based
  - Automated, self-calibrating
- Can not cheat on it
- Diagnostic and quantitative
- Scoring issue

Colour and Diagnostic Test (CAD Test)

- Developed by Dr. John Barbur
  - City University London
- Uses specific chromatic targets moving against changing background noise
  - Eliminates luminance effects
- Computer based
- Diagnostic and quantitative

Computerized Color Vision Test (CCVT)

- Developed by Dr. Terry Waggoner
- Uses random computer generated PIP plates
  - 29 plate screen
  - 76 plate diagnostic
- Computer based
  - Self-calibrating
- Diagnostic and quantitative
  - Limited experience

New USAF Color Vision Policy (January 2013)

- Rabin Cone Contrast Test (CCT)
  - Replaces PIP I in the field as primary color vision screener
- CCT failures may be pursued at USAFSAM
  - CCT, CAD, CCVT, Test Battery
  - Anomaloscope confirmation

“Color Correction” Lenses

- Red X-Chrom
- ColorView
- ColorMax
- Cantor & Silver 5X Tinted
- Coloryte
- ChromaGen
Gene Therapy

“Gene therapy for red-green colour blindness in adult primates.”

QUESTIONS?