Introduction to Colour Science

NPGR025

Unit 2: Human Perception

Computer Graphics Charles University

Sources:
R. Boynton, Human Color Vision
Welsch, Liebmann: Farben
Spektrum der Wissenschaft Spezial „Farbe“

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Overview

- The Physics Behind Colour
  - „Where colours actually come from“
  - Implications for colour reproduction technology
- Colour Perception
  - „How we see colour“
  - Implications for display technologies, in particular tone mapping
- Colorimetry & Colour Spaces
  - „How we can arrange colour“
  - How colour spaces relate to each other
  - Making sense of the colour space zoo out there

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Overview

- The Human Visual System
  - Eye anatomy
  - The visual pathway
  - Monochromatic vision
  - Colour vision
- Colour Blindness
- Alien Vision
- Optical Illusions

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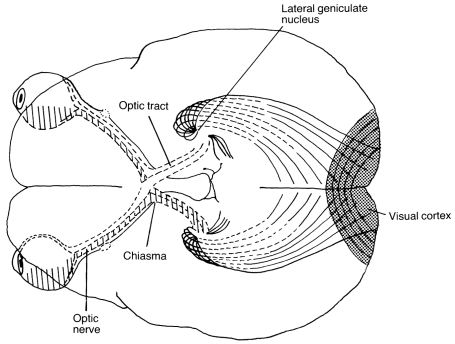
The Human Visual System

Human Visual System

- Principal sensory organ: the eyes
- By far the most data-intensive sense: estimates rank 80% of all input as visual
- Substantial post-processing of raw data necessary to yield insights
- Only exterior (processing) parts of the HVS are reasonably well understood
- Fortunately, these are those which are of immediate interest to colour science

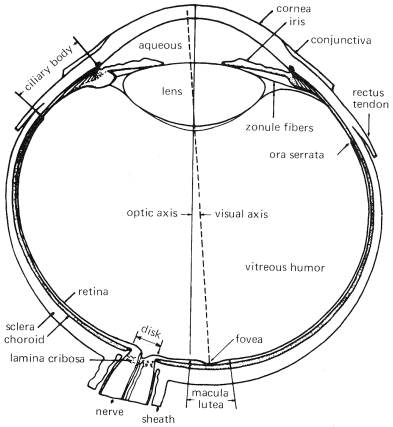
Visual Centres in the Brain

- Visual cortex is located at the rear of the skull
- Optical nerves cross once
- Exact functions of inner brain regions is still not entirely clear



Human Eye Anatomy

- Principle: inverted image is focused on the retina
- Simple optical system
- Large chromatic aberration
- Powerful retinal processing

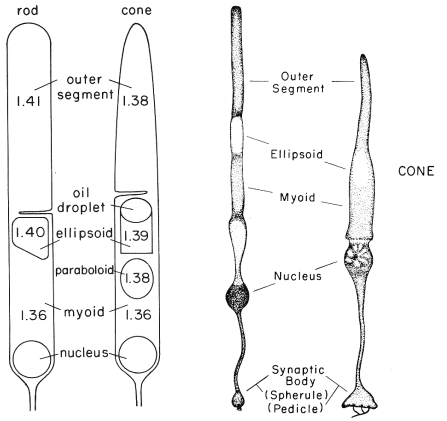


The Retina

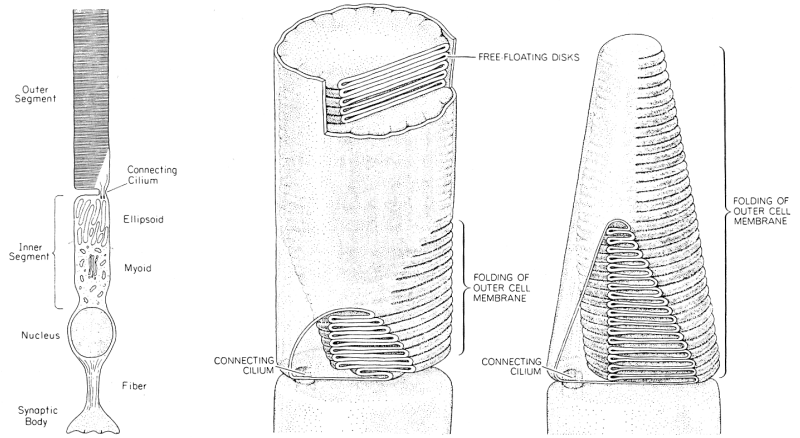
- The light-sensitive tissue onto which an image of the exterior is projected
- Two types of light-sensitive cells exist: rods and cones
- These are supported by
  - A large neural infrastructure that gathers their inputs
  - Support systems such as connecting tissue and blood vessels

Rods and Cones

- Specialised nerve cells with light-sensitive tips
- Can register single photons
- Humans can perceive > ~ 9 photons



Rod and Cone Detail

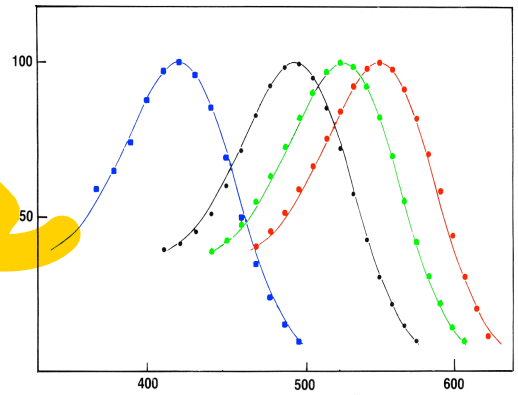


Rod and Cone Basics

- Incident photons are converted to neural stimuli through an electrochemical reaction called bleaching
- All four types of light-sensitive cell have their own photopigments, which are based on the same chromophoric group connected to an opsin protein molecule
- Rhodopsin – the rod pigment – is also called *visual purple* because it absorbs yellow/green light and transmits purple

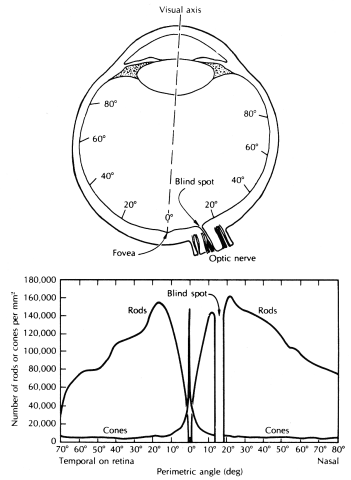
Receptor Absorbance

- Rods @ 496
- „Red“ L @ 558
- „Green“ M @ 531
- „Blue“ S @ 419
- Cone densities: 40 L : 20 M : 1 S
- Measured on dissected eyes



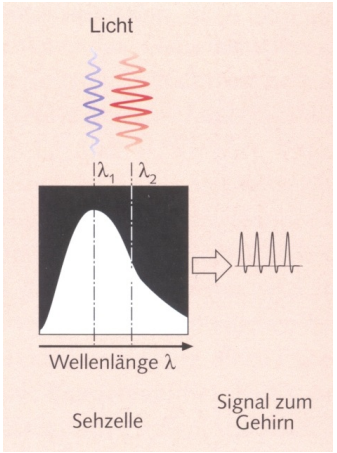
Rod and Cone Distribution

- The Fovea (the yellow spot) is the only area where humans really perceive substantial colour stimuli
- Outside the fovea the majority of cones are of the „blue“ S type
- Neural processing ensures smooth perception



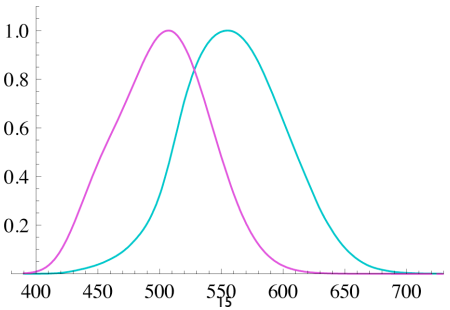
Equivalence of Stimuli

- Stimuli generate electric nerve signals proportional to input signal and sensitivity
- Example: weak blue light generates same response from blue cones as strong red light does



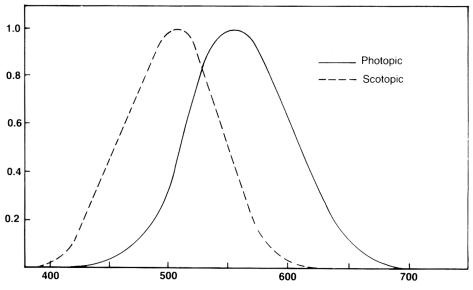
V(λ) and V'(λ)

- These functions describe how efficiently the eye responds to light of a given wavelength
  - V(λ) (cyan) - normal light levels (daytime)
  - V'(λ) (pink) - low light levels (night)



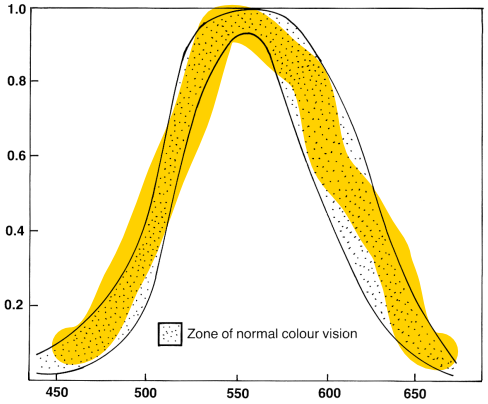
Relative Luminous Efficiency

- Photopic – adapted to daylight (cones, V(λ))
- Scotopic – adapted to the dark (rods, V'(λ))
- Mesopic – intermediate



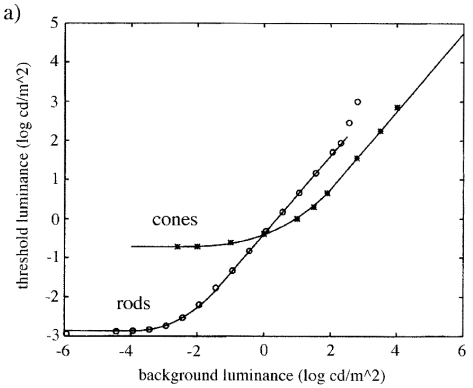
RLE Bandwidth

- Response curves are typically not exactly valid for all humans
- A wide gamut of „healthy“ RLE values exists
- Exact curve is partially age-dependent



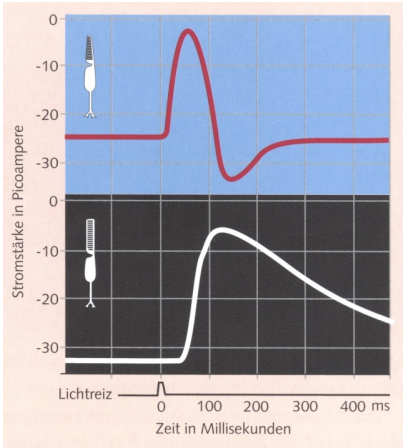
Rod vs. Cone Sensitivity

- Rods and cones serve two purposes:
- Rods are slower, but more sensitive to low light conditions
- Cones are capable of colour vision, but not at night



Rod vs. Cone Firing Characteristics

- Cones are less sensitive to light, but fire four times faster
- Rods are slower, but generate a longer signal

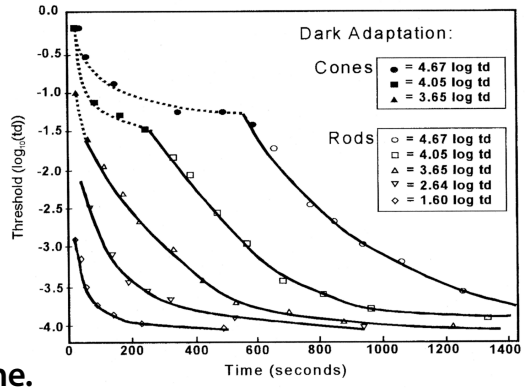


Temporal Behaviour

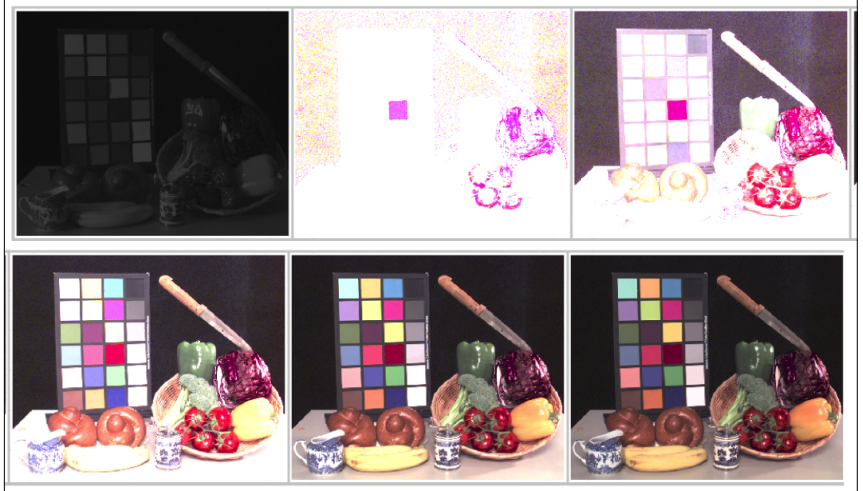
- Photopigments are bleached by incident photons, a chemical reaction which has to be reversed in order for a particular molecule to fire again
- The rods and cones have a certain regeneration speed for their pigments which is matched to the illumination
- A retina where a state of equilibrium w/r to use and regeneration of pigments has been reached is called adapted to the illumination

Dark Adaptation

- Cones are initially faster, but have a higher threshold
- Rods slowly take over after some time.

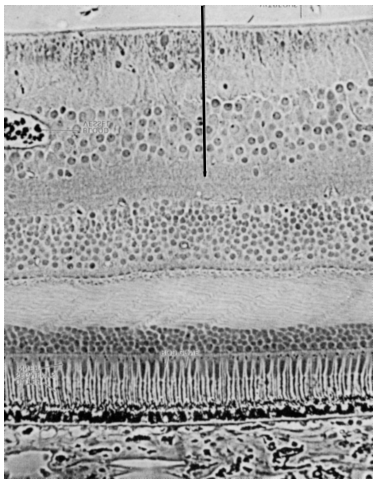


Time Dependent Perception



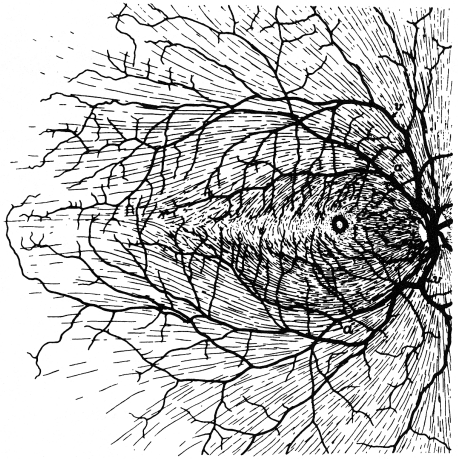
Retina Structure

- Rods and Cones lie behind a layer of support tissue and above a complex neural infrastructure
- Rods are used for achromatic vision
- The 3 subtypes of cones are responsible for colour vision



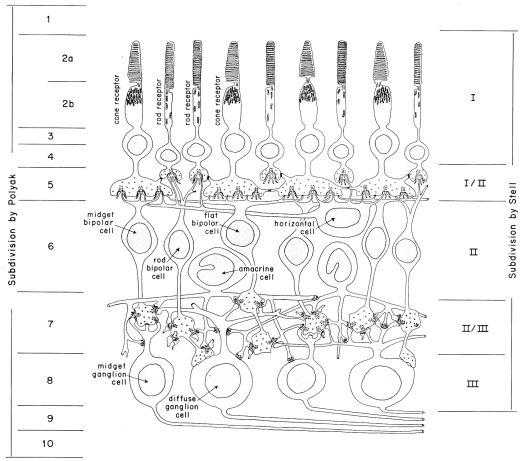
Retinal Blood Vessels

- Pattern of blood vessels in the retina is as characteristic as a fingerprint
- Used in modern biometric authentication systems

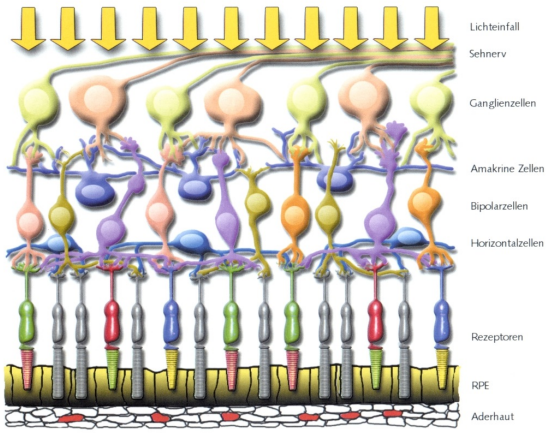


Retinal Interconnections

- Single layer of rods and cones
- Multiple levels of inter-connections
- Ganglions as final step

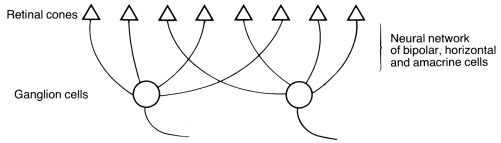


Retinal Structure #2

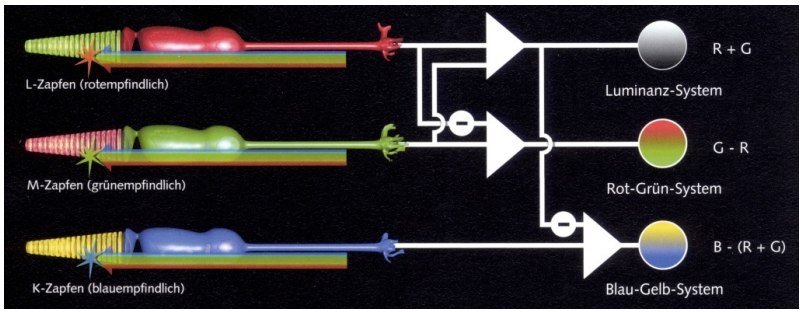


Neural Processing in the Retina

- Rods and Cones are mutually inter-connected to perform pre-processing tasks
  - Edge enhancement
  - Colour separation (spectral inhibition)
  - Separate „wiring“ for rods and cones
- ~150M rods & cones versus ~1M ganglion cells



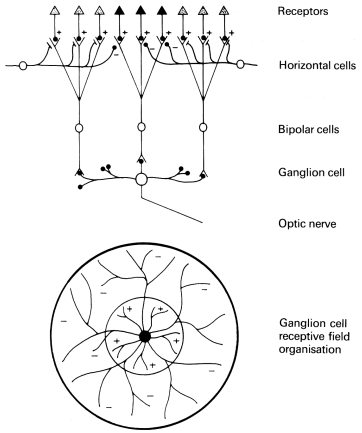
Post-processing System



- Bridge between LMS sensors and separate perception of luminance and chroma (L*a*b)

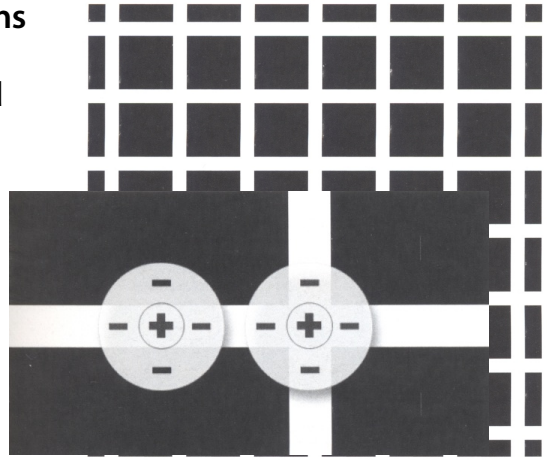
Ganglion Receptive Field

- Groups of receptors are bundled to provide specific edge-detection capabilities
- Opponency capabilities are particularly well developed for luminance processing



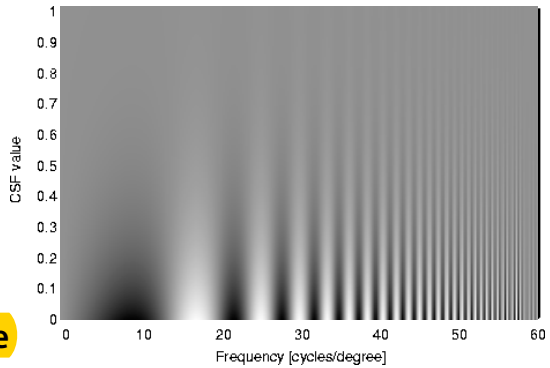
Hermann Grid

- Similar patterns work for red/green and blue/yellow
- Can be explained through inhibition mechanisms



Contrast Sensitivity

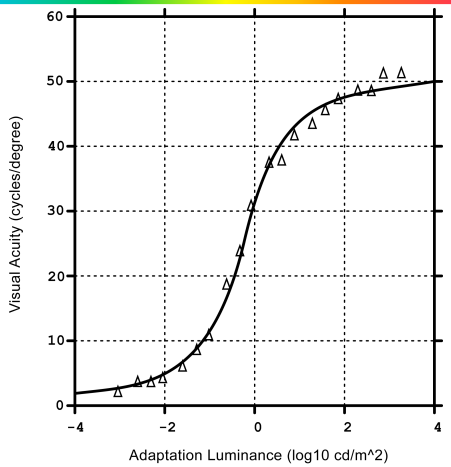
- Dependent on density and arrangement of rods and cones in the retina
- Peak at about 8 cycles/degree
- Zero above 60 cycles/degree



$$A(f) = 2.6 \cdot (0.0192 + 0.114 \cdot f) \cdot e^{-(0.114 \cdot f)^{1.1}}$$

Visual Acuity

- The ability to discern detail in a scene is dependent of the absolute intensity of the illumination
- At low light levels, rods take over



Rod vs. Cone Vision

Rod vision: colouless, blurred

Cone vision: sharp, colour

HL Neural Processing: Colour Constancy

Metamerism

Metamerism

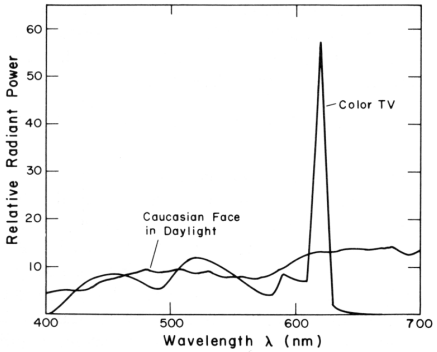
- Two complex stimuli P1λ and P2λ are in colour match if all three following equations hold:

$$\int P_{1\lambda} r(\lambda) d\lambda = \int P_{2\lambda} r(\lambda) d\lambda$$
$$\int P_{1\lambda} g(\lambda) d\lambda = \int P_{2\lambda} g(\lambda) d\lambda$$
$$\int P_{1\lambda} b(\lambda) d\lambda = \int P_{2\lambda} b(\lambda) d\lambda$$

- Under certain constraints the two stimuli can have completely different spectral distributions!
- P1λ and P2λ are called metameric stimuli, or just metamers

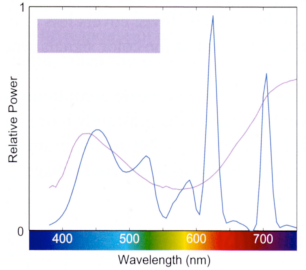
Metamerism

- Contrary to what one might expect, this phenomenon occurs frequently in real life
- Especially on (but not limited to) RGB monitors
- Also one of the most interesting problems in the paint and pigment industry

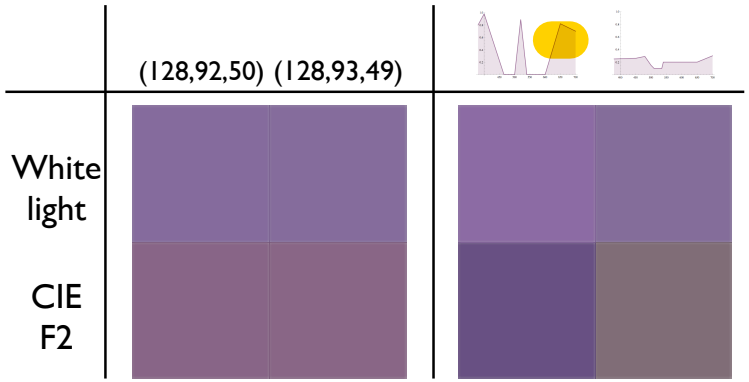


Printer Metamerism

- M. is generally not very problematic for additive output devices
- If the "wrong" pigments or dyes are chosen, M. can significantly impair the ability of printers to produce good colour output
- Affects all types to some degree – matches are only possible for a given illuminant!



RGB vs. Spectral: Metamerism



Metamerism Example

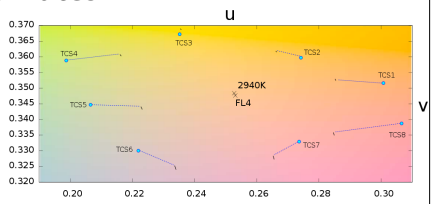
Observer Metamerism

Metamerism: Proper Usage

- Two stimuli are said to be *metameric* to each other if they differ in their spectral composition, but are perceptually indistinguishable
- If the circumstances of observation change (change of lightsource, change of observer), and the two no longer match, one should properly speak of a *metameric failure* occurring.

Measuring Metamerism: CRI

- The Colour Rendering Index (CRI) is a measure of how faithfully a given lightsource reproduces colours
- Idea: a set of standardised colours is observed under a reference illuminant, and the illuminant one wants to know the CRI for
  - Compare CIE u,v coordinates
  - This includes white adaptation!
  - Not meaningful for colourful light



CRI Test Samples

- Taken from an older edition of the Munsell Book of Colours
- Samples no longer physically available
  - Modern Munsell Book of Colours only contains metamers

Name	Appr. Munsell	Appearance under daylight	Swatch
TCS01	7,5 R 6/4	Light greyish red	
TCS02	5 Y 6/4	Dark greyish yellow	
TCS03	5 GY 6/8	Strong yellow green	
TCS04	2,5 G 6/6	Moderate yellowish green	
TCS05	10 BG 6/4	Light bluish green	
TCS06	5 PB 6/8	Light blue	
TCS07	2,5 P 6/8	Light violet	
TCS08	10 P 6/8	Light reddish purple	
TCS09	4,5 R 4/13	Strong red	
TCS10	5 Y 8/10	Strong yellow	
TCS11	4,5 G 5/8	Strong green	
TCS12	3 PB 3/11	Strong blue	
TCS13	5 YR 8/4	Light yellowish pink	
TCS14	5 GY 4/4	Moderate olive green	

CRI: Examples

Light source	CCT (K)	CRI
Low Pressure Sodium (LPS/SOX)	1800	~5
Clear Mercury-vapor	6410	17
High Pressure Sodium (HPS/SON)	2100	24
Coated Mercury-vapor	3600	49
Halophosphate Warm White Fluorescent	**2940**	**51**
Halophosphate Cool White fluorescent	4230	64
Tri-phosphor Warm White Fluorescent	2940	73
Halophosphate Cool Daylight Fluorescent	6430	76
"White" SON	2700	82
Quartz Metal Halide	4200	85
Tri-phosphor Cool White fluorescent	4080	89
Ceramic Metal Halide	5400	96
Incandescent/Halogen Light Bulb	3200	100

Types of Metameric Failure

- Sample / Illuminant Metameric Failure
  - Objects that look alike under one illuminant have dissimilar appearance under another
- Observer Metameric Failure
  - When objects that look alike for human observers do not match for other observers
  - *An issue for digital cameras / film / other species!*
- Geometric Metameric Failure
  - Colours that look alike under a certain viewing angle no longer match when viewed under a different angle

Metameric Black Construction

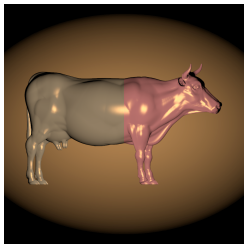
- Idea: for a given light L(λ), construct a synthetic reflectance spectrum r(λ) so that the sum of

$$r(\lambda) * L(\lambda) * Oi(\lambda)$$

  is zero when summed over all wavelengths λ, for all three matching functions Oi(λ)
- Under-constrained problem, infinitely many solutions
- Synthetic spectrum will be positive and negative
- Add to real reflectance for "real" metamers

Metacow: Test Image

- Synthetic image for imaging system research / testing
- Basically, a large number of cows with two halves that have different spectral reflectances:
  - Left: Macbeth Colour checker
  - Right: maximally metameric to the left side
  - *Note: the right sides usually do not correspond to reflectances that you could realise in practice!*
- http://www.cis.rit.edu/mcsl/METACOW/



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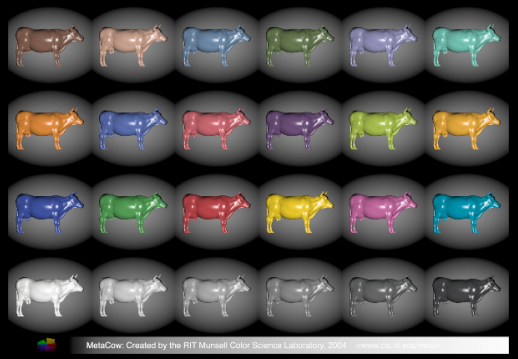
Metacow: Human Observer



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Metacow: Human Observer

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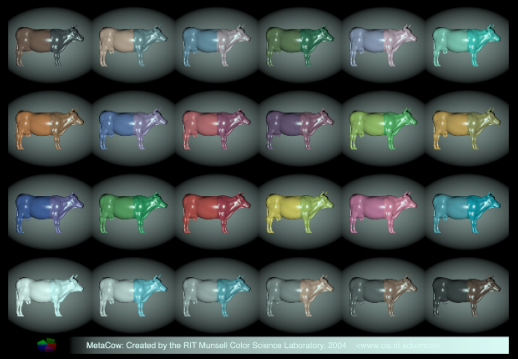
Metacow: Canon Digicam



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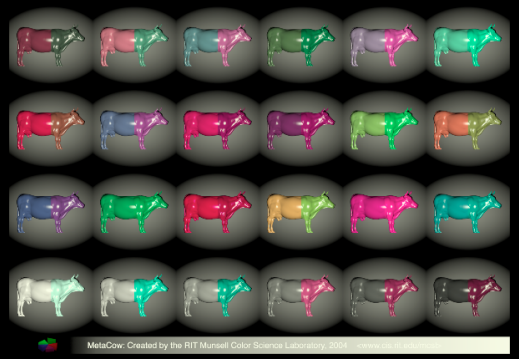
Metacow: Canon Digicam



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Metacow: Chemical Film

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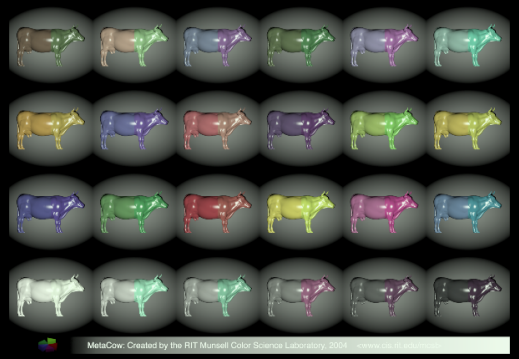
Metacow: Chemical Film



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Colour Blindness

Colour Blindness 1

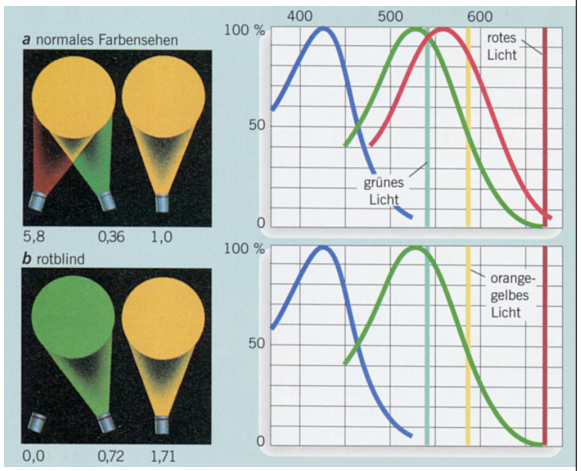
- Recessive trait, located on X-chromosome
- Much more likely to occur in males than in females (1 in 5-10 males have deficiencies)
- Several types of CB exist, depending on which part of colour perception is not present
- Most common form is red-green blindness
- Names: Daltonism, after its discoverer, protanopia (missing „red“ pigments) or deuteranopia (missing „green“ pigments)

Colour Blindness 2

- Blue-yellow blindness (tritanope, no „blue“ pigments) is much rarer, and equally distributed across males and females
- Complete colour blindness (no spectrally selective opsins at all) is very rare
- Apart from colour test charts, anomaloscopes are used to test for the various forms of CB
- In the population there also exist certain natural variations in the absorption characteristics of the pigments

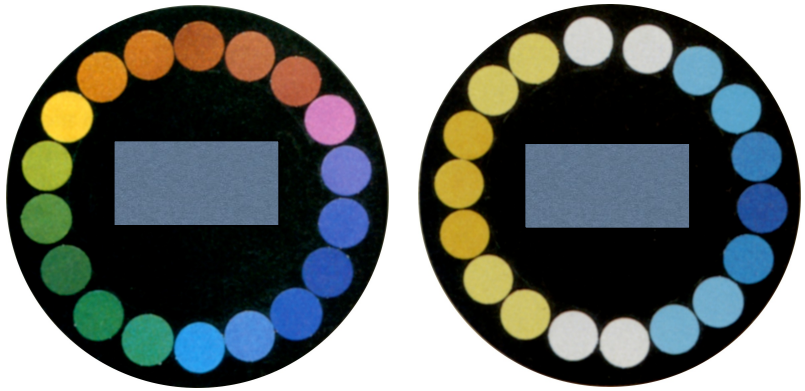
Anomaloscope

- Mini colour matching experiment
- Subject has to mix red and green to match a given mono-chrome light



CB Colour Circle

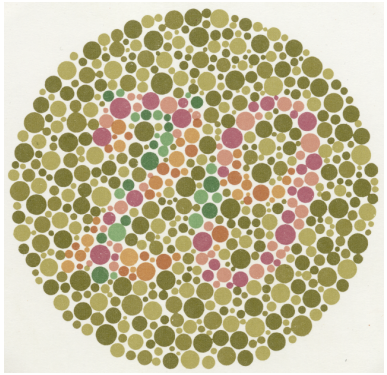
- For red-green blindness vs. „normal“

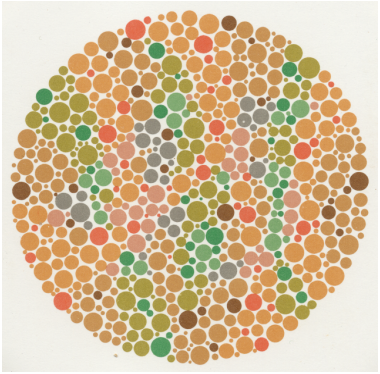


CB Painting

CB Copy of a Painting

Colour Deficiency Test Plates





„Alien Vision“

Images taken from:

Alien Vision: Exploring the Electromagnetic Spectrum with Imaging Technology

Austin Richards

SPIE Press

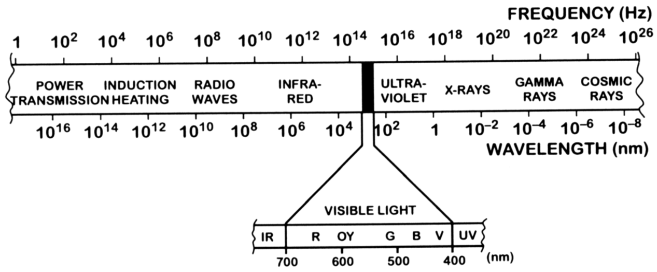
http://www.alienvision.org/

Multi-Spectral Imaging

- A short tour that demonstrates a visual world this lecture is not about
- Modern imaging devices permit us to „see“ in areas of the electromagnetic spectrum for which humans do not have any sensory organs
- Everyday objects sometimes exhibit strange appearance attributes when viewed in non-visible wavebands

Light – Basic Properties

- Visible light is electromagnetic radiation in a particular region of the entire spectrum
- Distinguishing criterion: its frequency



Infrared Taxonomy

- Main differences lie in technology needed to image the area and in the „plausibility“ of the images

Visible	Near-IR	SWIR	MWIR	LWIR
0.4 - 0.75 μm	0.75-1.1 μm	1.1-2.5 μm	2.5-7 μm	7-15 μm

Increasing Wavelength →

Polar Bears in near UV

Person in IR – VIS – UV

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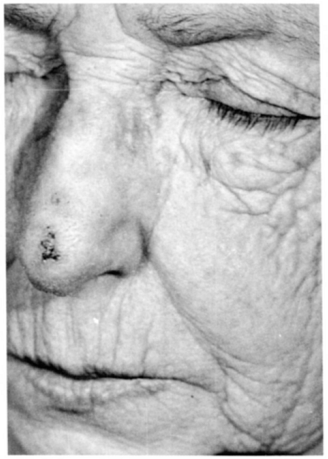
Near UV Medical Imaging



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Near IR and UV imaging

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„Anomalous“ Near IR Image

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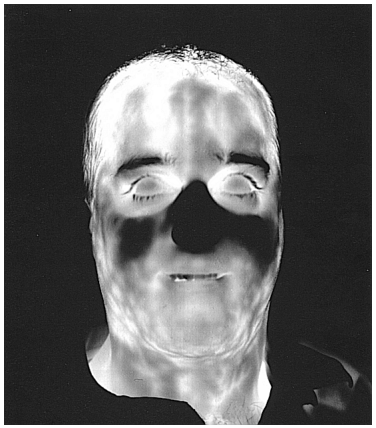
Insect Vision: Near UV

Medium and Long Wave IR

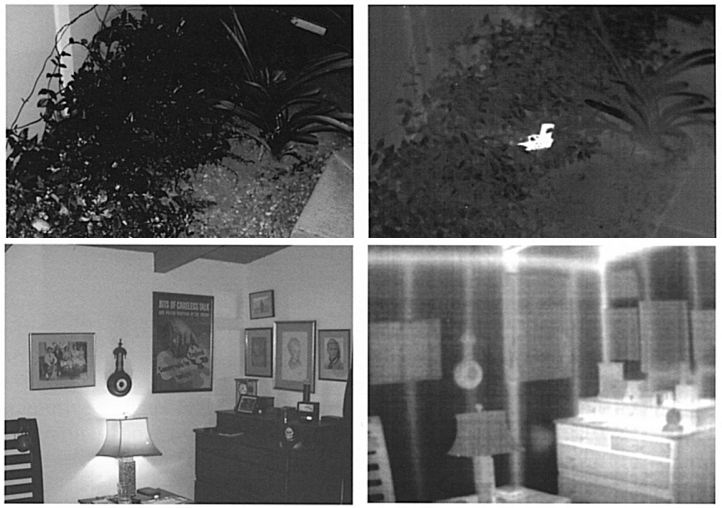
- Non-standard imaging equipment needed
- M/LWIR video equipment is comparatively recent technology
- MWIR cameras have metal lenses which are totally opaque to visible light
- Cooling is necessary for their CCD elements

MWIR Examples #1

MWIR Examples #2



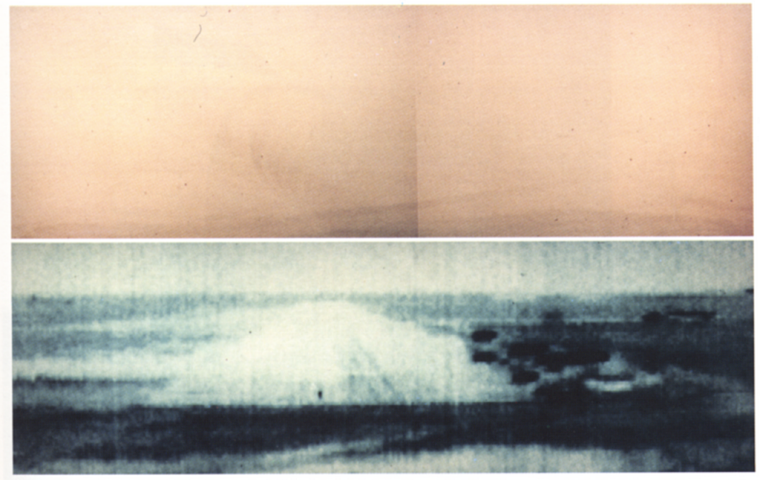
LWIR Examples



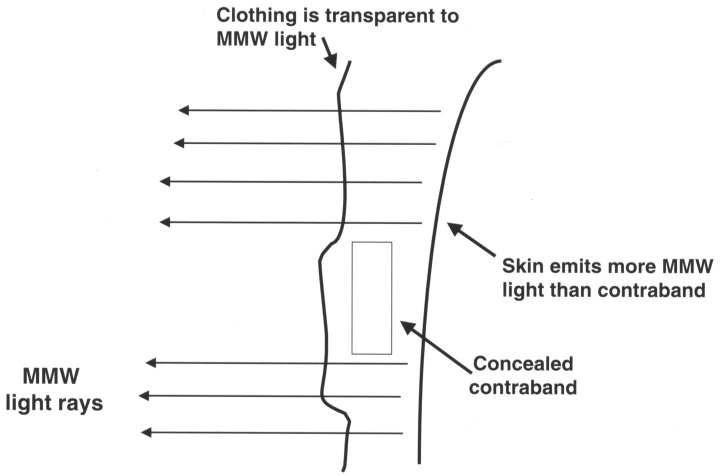
Millimetre Wave Imaging

- Recent Development
- Penetrates Clothing and Fog
- Passive, not harmful
- Emitted by the human skin
- Current Problems:
  - Low resolution
  - Low framerate
- Plastic lenses used in production cameras

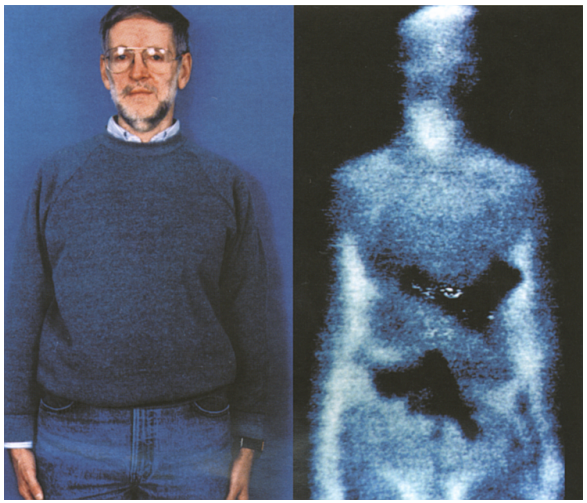
MMW Application: Approach



MMW Security: Principle

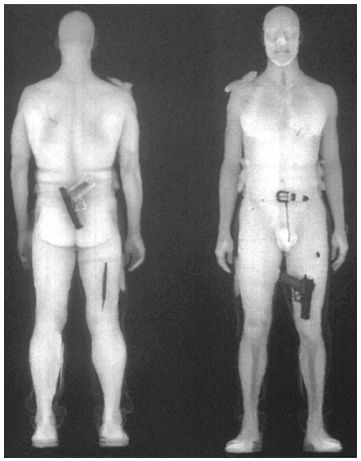


MMW Security: Example



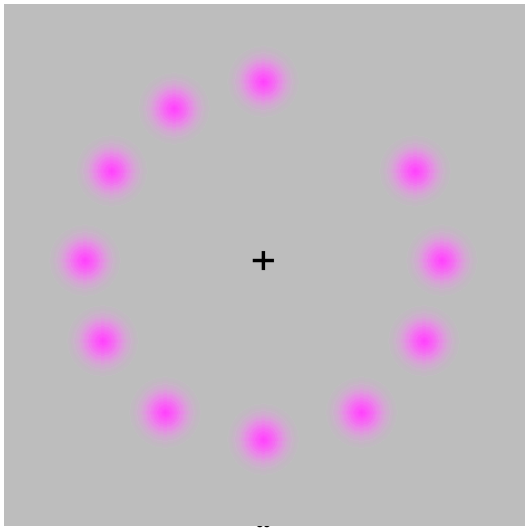
X-Ray Backscatter

- Backscatter of X-rays from certain types of tissue is imaged
- Penetrates all types of clothing and cover
- Use on humans not harmful, but still raises ethical questions

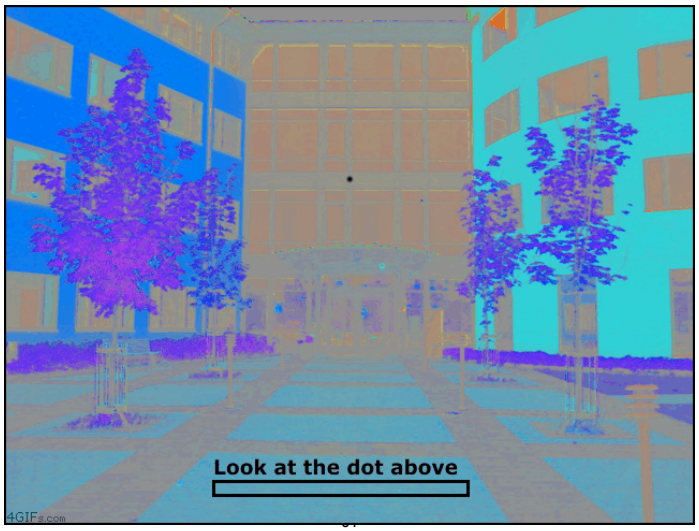


Optical Illusions

Keep looking at the center



Look at the dot



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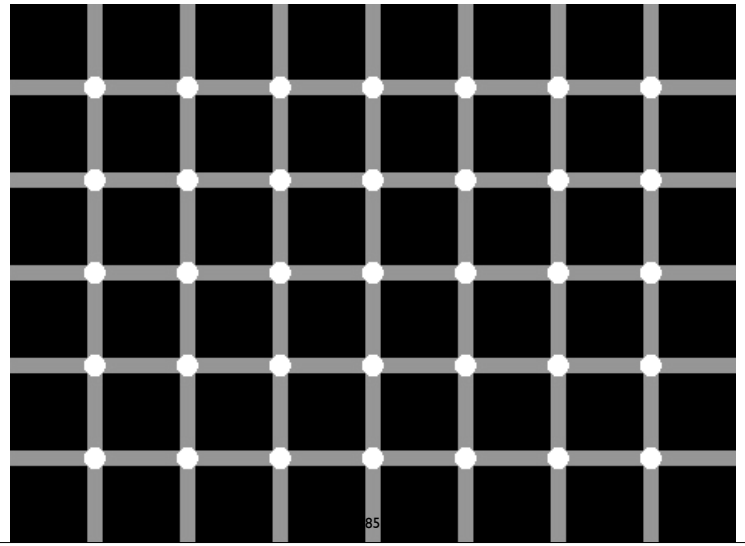
Count the black dots



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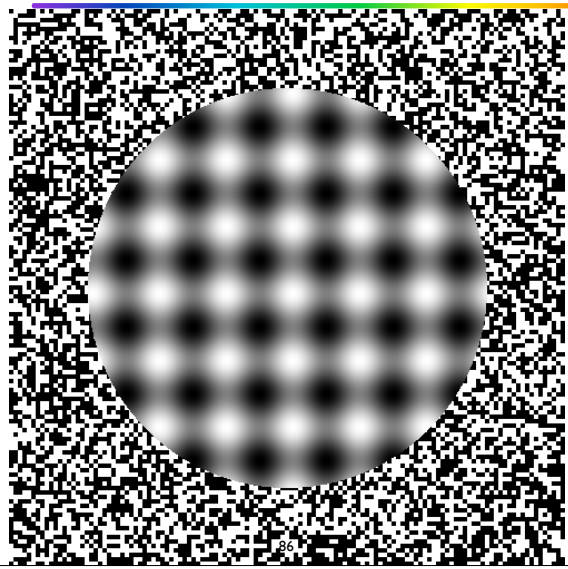

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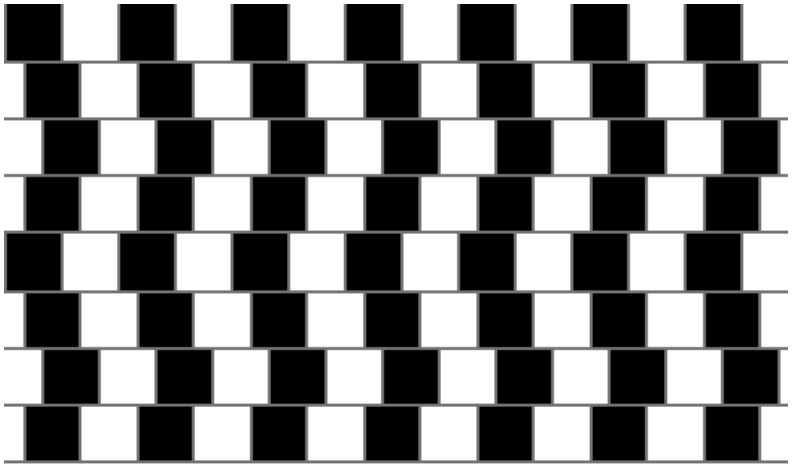
Are the horizontal lines straight?



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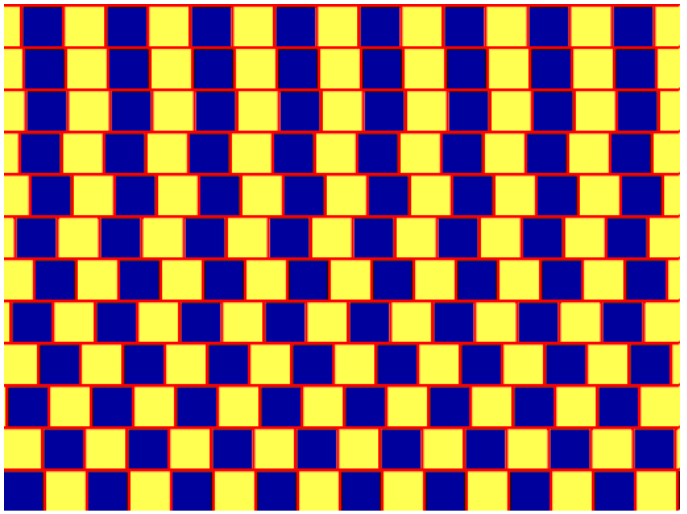

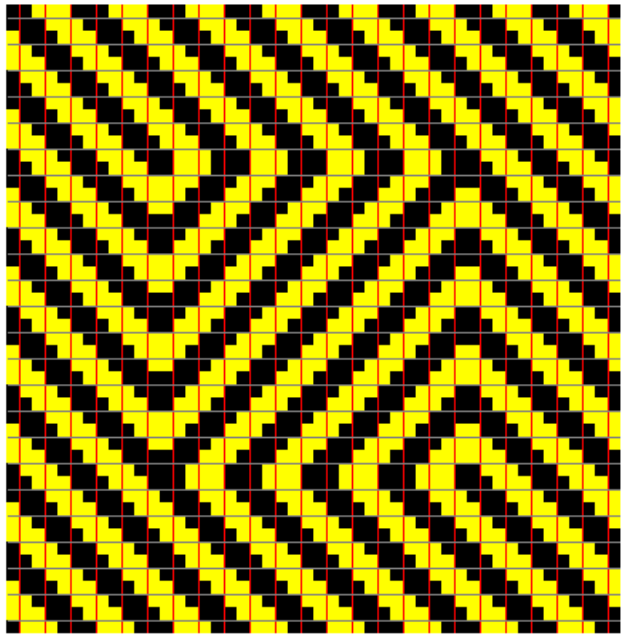

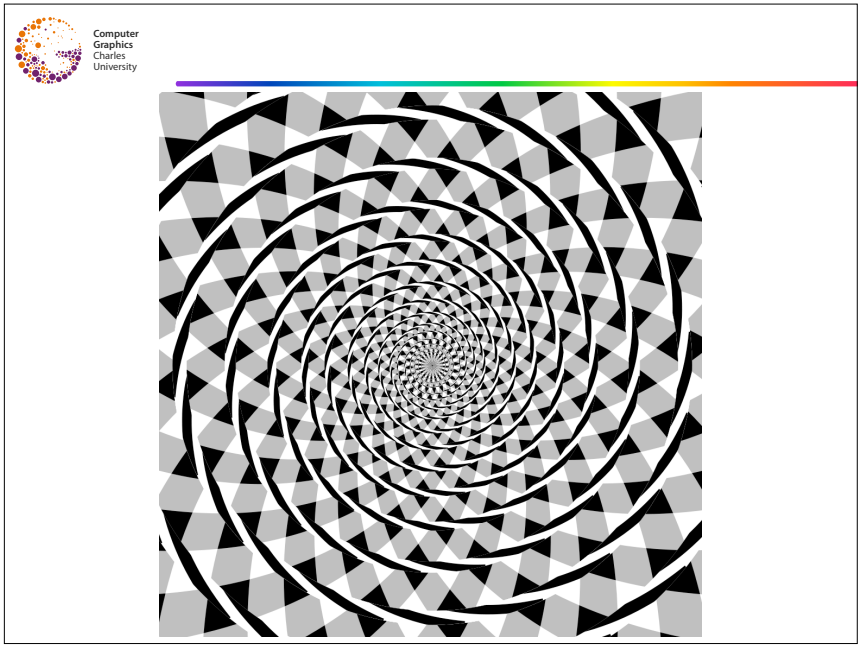
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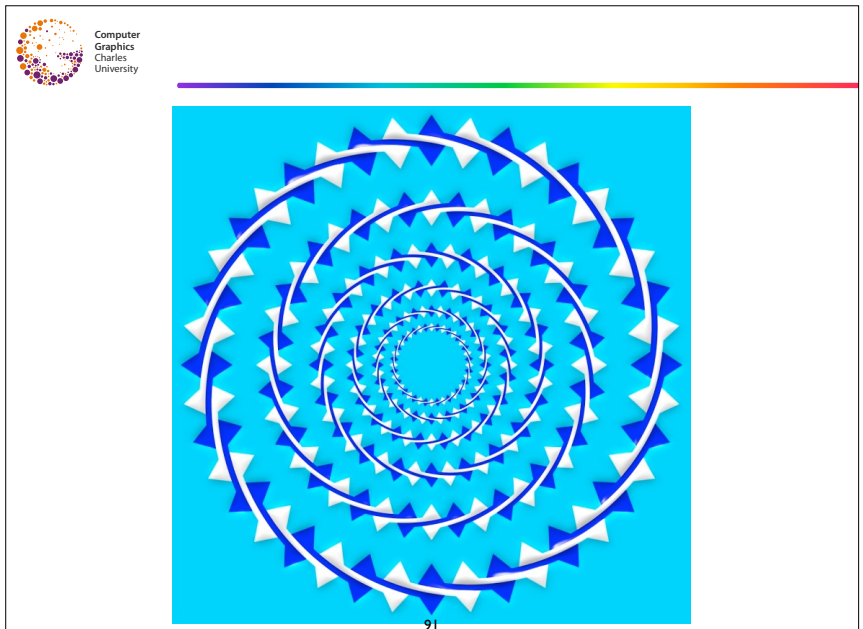
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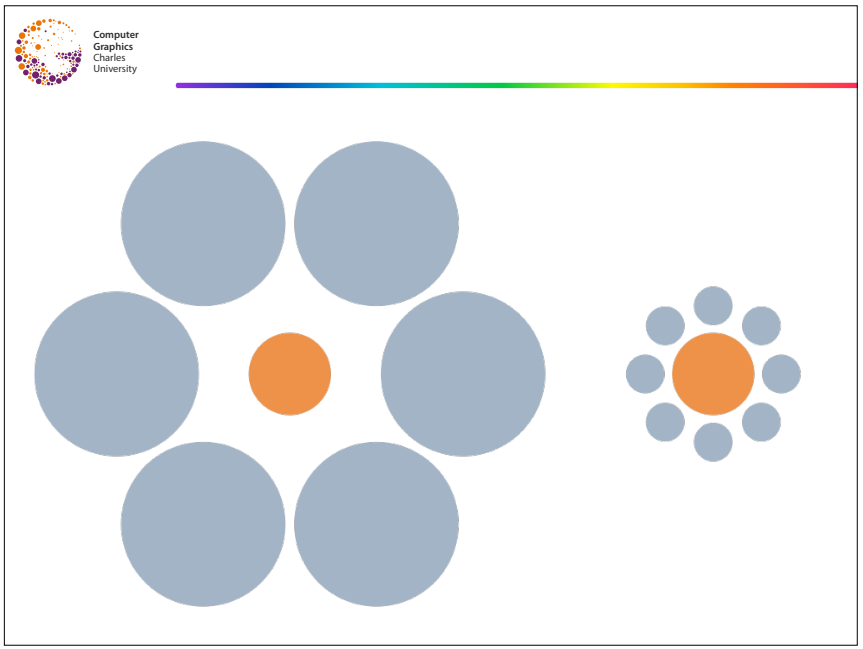
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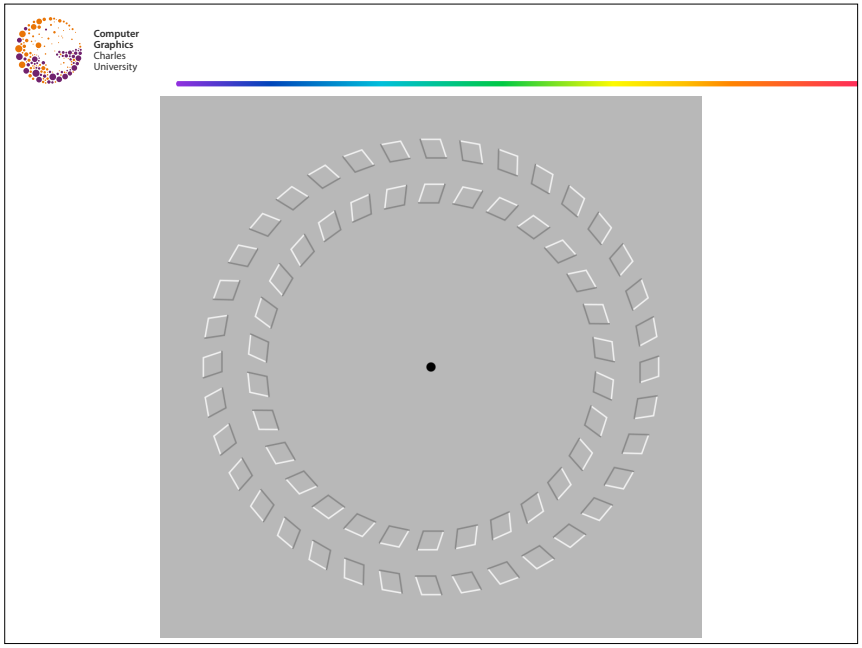
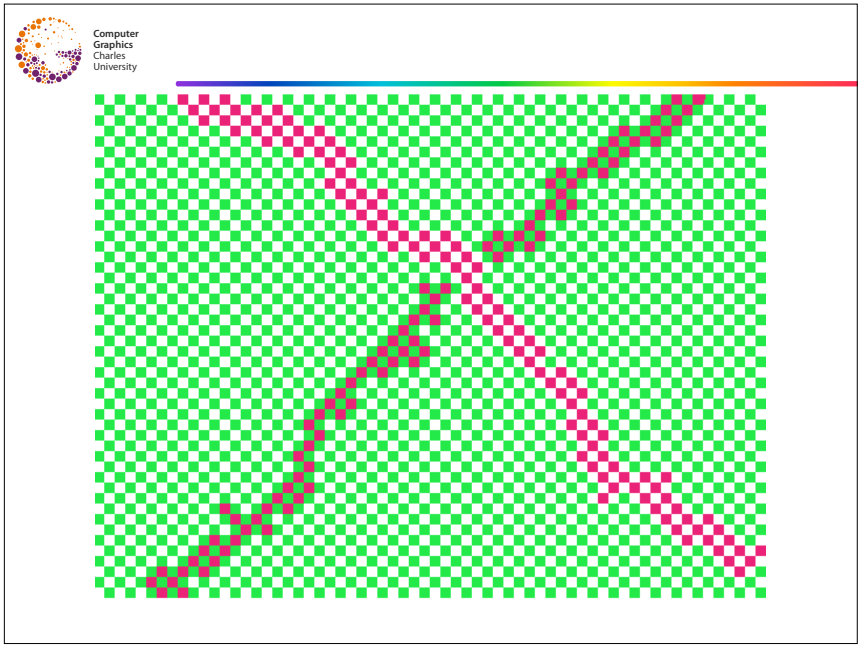
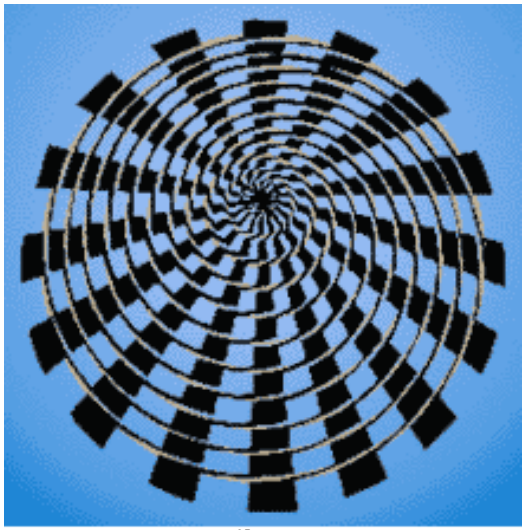
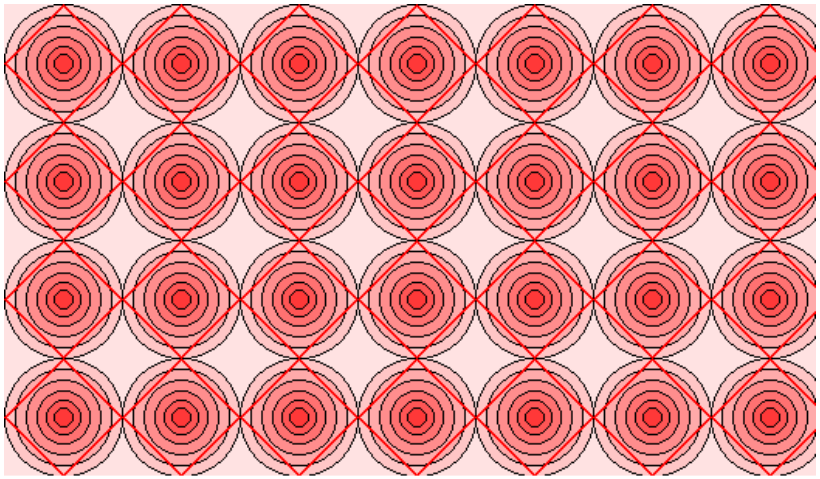
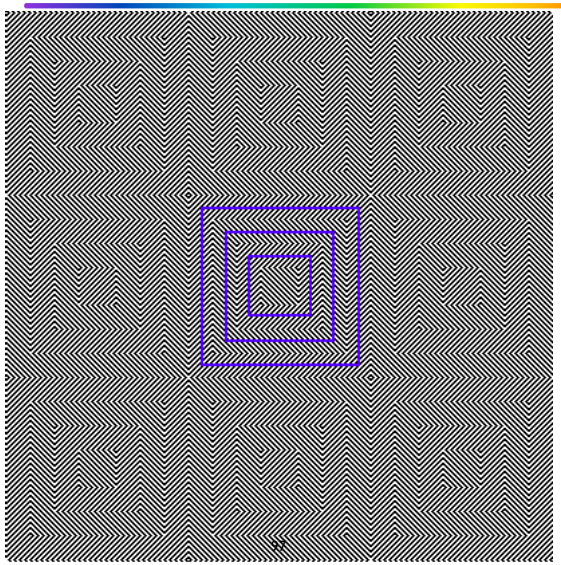






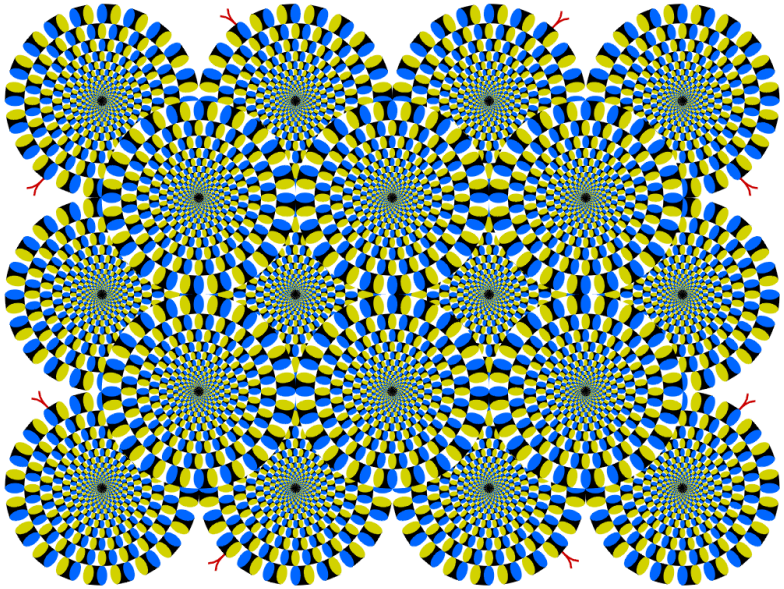


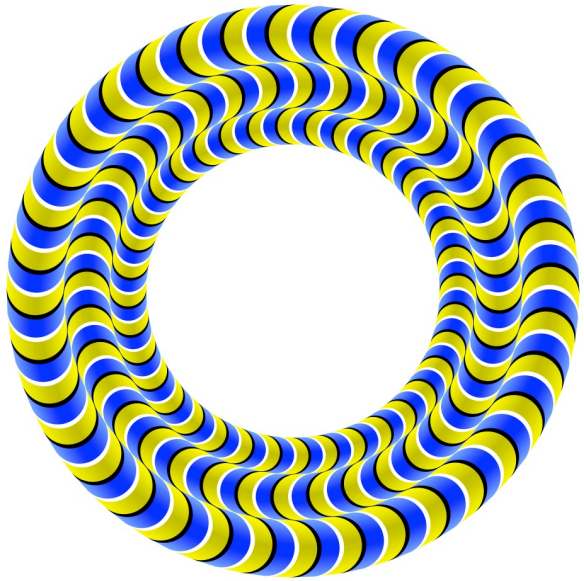


(video)

Anomalous Motion Illusions

- Caused by
  - Involuntary eye movements
  - Hardwired edge and movement detection „circuitry“ in the retina
- Many more images at:
  - http://www.ritsumei.ac.jp/~akitaoka/index-e.html





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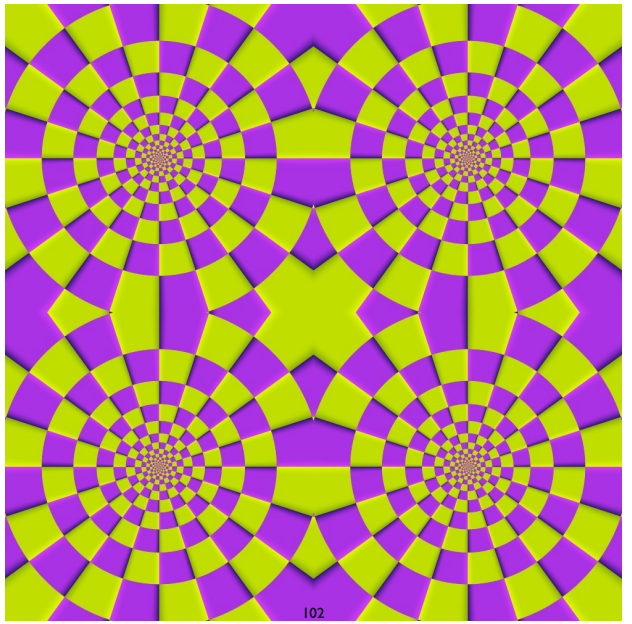

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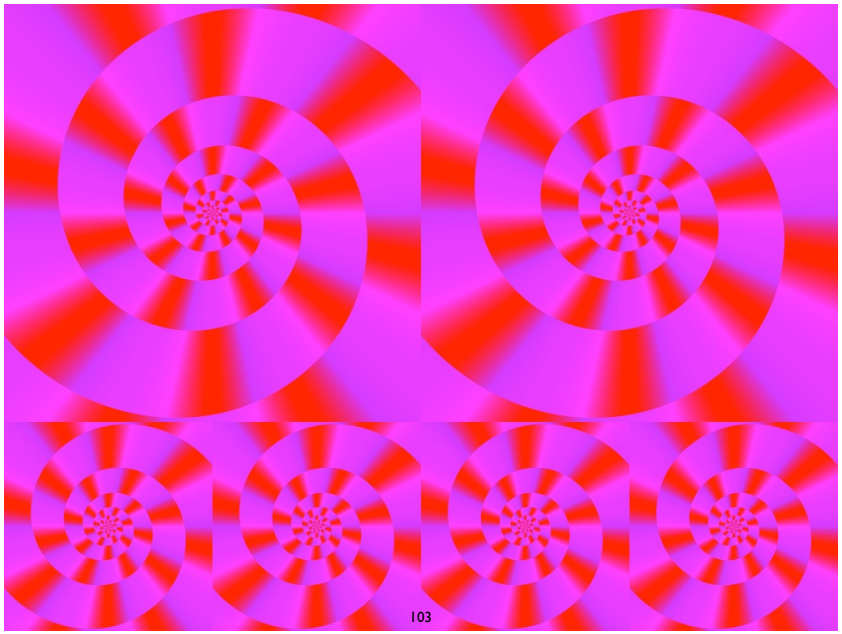

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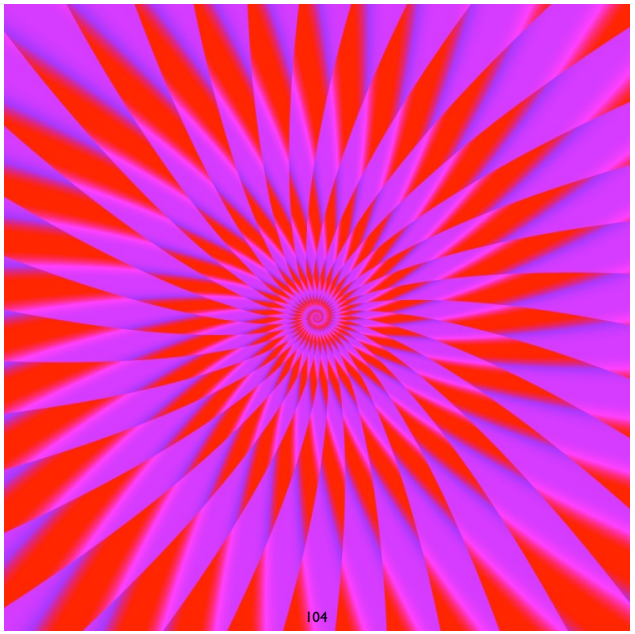

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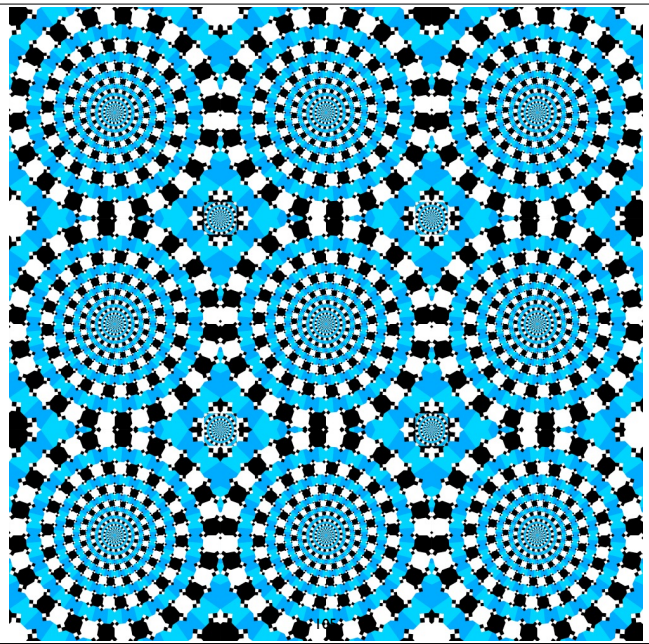

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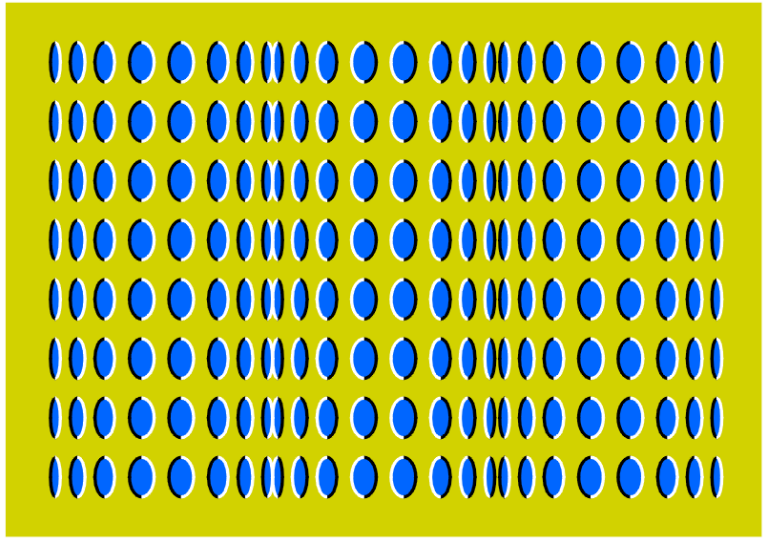

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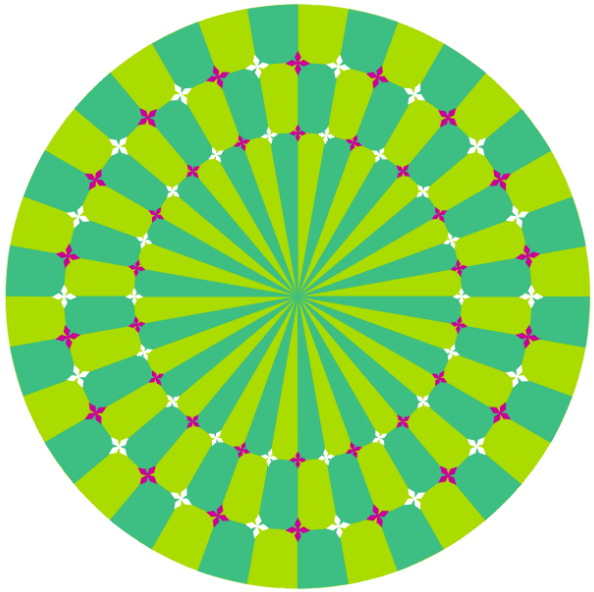

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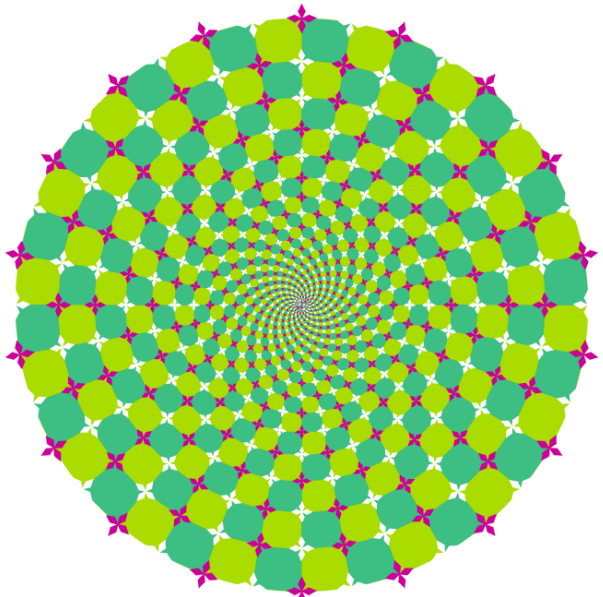

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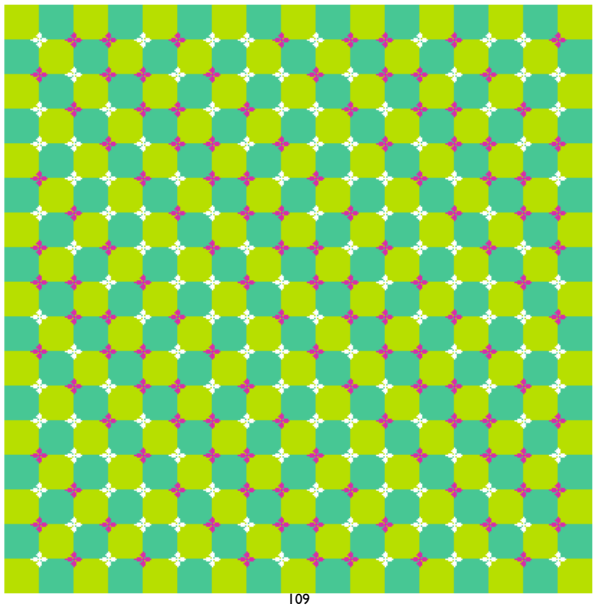

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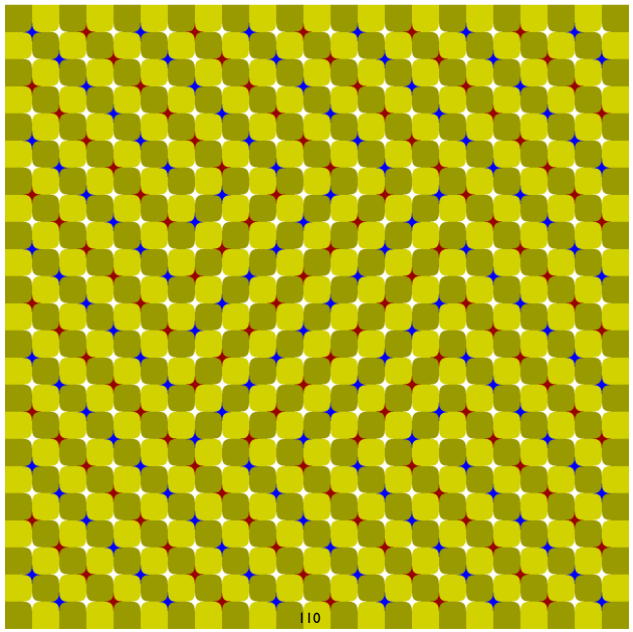

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