What Is Color? How Brains Make Color Sensations

Contents

Abstract

Brain transforms perceptual properties into patterns and motions of geometric-algebra vectors, making microscopic surface textures whose spatial and temporal properties are sensory experiences.

Keywords

accommodation, aftereffect, ambiguous figure, binocular disparity, binocular rivalry, binocular vision, blindsight, blinking, brightness, change blindness, color, color space, color wheel, complementary colors, cone, contancy, contour, contrast, cortex, dark adaptation, depth, depth cue, distance, eye, filling-in, fixation, focusing, ganglion cell, gestalt, Grassman laws, hue, illusion, intensity, lateral geniculate, lesion, lightness, luminance, mental rotation, midbrain, mirror reversal, motion parallax, number perception, optic flow, pattern recognition, primary color, pure color, qualia, receptor, retina, rod, saccade, saturation, size perception, spectral color, texture perception, univariance, viewpoint, visual search

1. Anatomy

Eye has retina, and retinal cells send visual information to thalamus and visual cortex.

1.1. Eye

Land-vertebrate eyes are spherical and have layers.

1.1.1. Eyeball layers

Eyeball has outer white opaque connective-tissue layer {sclera}. Eyeball regions {trochlea} can have eye muscles. Eyeball has inner blood-vessel layer {choroid}. Eyeball has an inside space {fundus} filled with fluid.

1.1.2. Eyeball front

Eye has transparent cells {cornea} protruding in front. Cornea has no blood vessels and absorbs nutrients from aqueous humor. Cornea has many nerves. Corneas can transplant without rejection.

Elastic and transparent cell layers {lens} {crystalline lens} attach to ciliary muscles that change lens shape. To become transparent, lens cells destroy all cell organelles, leaving only protein {crystallin} and outer membrane. Lens cells align and interlock [Weale, 1978].

Eye has opening {pupil} into eye. In bright light, pupil is 2 mm diameter. At twilight, pupil is 10 mm diameter.

Sphincter muscles in a ring {iris} close pupils. When iris is translucent, light scattering causes blue color. When iris is opaque, color is brown. In mammals, smooth muscles (and autonomic nervous system) control control pupil opening. In birds, striate muscles control pupil opening.

1.1.3. Fluids

Liquid {aqueous humor} in anterior chamber behind cornea nourishes cornea and lens.

Liquid {vitreous humor} fills main eyeball chamber between lens and retina.

1.1.4. Eye muscles

Midbrain oculomotor nucleus sends, in oculomotor nerve, to inferior oblique muscle below eyeball, superior rectus muscle above eyeball, inferior rectus muscle below eyeball, and medial rectus muscle on inside.

Pons abducens nucleus sends, in abducens nerve, to lateral rectus muscle on outside of eyeball.

Caudal midbrain trochlear nucleus sends, in trochlear nerve, to superior oblique muscle that goes around above eyeball.

1.1.5. Eyelids

Most mammals and birds have a tissue fold {inner eyelid} {palpebra tertia} that, when eye retracts, comes down from above eye to cover cornea. Inner eyelid has outside mucous membrane {conjunctiva}, inner-side lymphoid follicles, and lacrimal gland.

Reptiles and some other vertebrates have transparent membrane {nictitating membrane} that can cover and uncover eye.

1.1.6. Retina

At back inner eyeball, visual receptor-cell layers {retina} have 90 million rod cells, one million cone cells, and one million optic-nerve axons. Retina has clusters of same cone-cell type. Retina areas can lack cone-cell types.

Primates have a central retinal region {fovea} that tracks motions and detects self-motion. Fovea contains 10,000 neurons in a two-degree circle. Fovea has no rods. Fovea has few short-wavelength cones. Fovea has patches of only medium-wavelength cones or only long-wavelength cones. Fovea has no blood vessels.

Retinal periphery detects spatial orientation.

Near retina center is a yellow-pigmented region {macula lutea} {yellow spot}. Yellow pigment increases with age.

Ganglion-cell axons leave retina at a region {blindspot} medial to fovea [DeWeerd et al., 1995] [Finger, 1994] [Fiorani, 1992] [Komatsu and Murakami, 1994] [Komatsu et al., 2000] [Murakami et al., 1997].

Ten retinal layers {inner plexiform layer} can have bipolar-cell and amacrine-cell axons and ganglion-cell dendrites. Between retina and choroid is a cell layer {retinal pigment epithelium} (RPE) and a membrane {Bruch's membrane} {Bruch membrane}.

Retina grows by adding cell rings to periphery. Oldest eye part is at center, near where optic-nerve fibers leave retina.

1.1.6.1. Receptors

Retina has pigment cells {photoreceptor cell}, with three layers: cell nucleus, then inner segment, and then outer segment with photopigment.

Human vision uses four receptor types: rods, long-wavelength cones, middle-wavelength cones, and short-wavelength cones.

Retina has 90 million rod-shaped retinal cells {rod cell}. Rods have cell nucleus layer, inner layer that makes pigment, and outer layer that stores pigment. Outer layer is next to pigment epithelium at eyeball back. Rods are larger than cones. Rod light-absorbing pigment is rhodopsin. Fovea has no rod cells. Rod cells are denser around fovea. Many animals have only rods {rod monochromat} and cannot see color.

1.1.6.2. Cones

Cone-shaped retinal cells {cone cell} have daylight-vision photoreceptors. Cone light-absorbing pigment is iodopsin. Humans have three cone types. Shrimp can have eleven cone types.

Cones are smaller than rods.

Cones send to one ON-center and one OFF-center midget ganglion cell.

There are five million cones, mostly in fovea. Fovea has patches of only medium-wavelength or only long-wavelength cones. Fovea has few short-wavelength cones, and fovea center has no short-wavelength cones. Short-wavelength cones are in periphery.

Long-wavelength cones evolved first. Long-wavelength and short-wavelength cones differentiated 30,000,000 years ago. Middle-wavelength cones began when primates began, so three cone types and trichromatic vision began in Old World monkeys.

Animals can have only one photopigment and one cone type {monochromat} {cone monochromat}. They have limited color range.

Most mammals, including cats and dogs, have two photopigments and two cone types {dichromat}. For dogs, one photopigment has maximum sensitivity at 429 nm, and one photopigment has maximum sensitivity at 555 nm. Early mammals and most mammals are at 424 nm and 560 nm.

People with normal color vision have three different photopigments and cones {trichromat}.

Women can have two different long-wavelength cones {L-cone} {L photopigment}, one short-wavelength cone {S-cone} {S photopigment}, and one middle-wavelength cone {M-cone} {M photopigment}, and so have four different pigments {tetrachromacy}. Half of men have one or the other long-wavelength cone [Asenjo et al., 1994] [Jameson et al., 2001] [Jordan and Mollon, 1993] [Nathans, 1999].

Reptiles and birds have four different photopigments {quadchromat}, with maximum sensitivities at near-ultraviolet 370 nm, 445 nm, 500 nm, and 565 nm. Reptiles and birds have yellow, red, and colorless oil droplets, which make wavelength range less, except for ultraviolet sensor.

1.1.6.3. Color-receptor array

Fovea has alternating Long-wavelength and Middle-wavelength cones in all directions: ...-L-M-L-M-.

Outside fovea, cones can form two-dimensional arrays {color-receptor array} with Long-wavelength, Middle-wavelength, and Short-wavelength cones in equilateral triangles. Receptor rows have ...S-M-L-S-M-L-S... Receptor rows above, and receptor rows below, are offset a half step: ...-L-S-M-L-S-M-.../...S-M-L-S-M-L-S.../...-L-S-M-L-S-M-... Cones have six different cones around them, in hexagons: three of one cone and three of other cone. No matter what order the three cones have, ...S-M-L-S-M..., ...S-L-M-S-L..., or ...M-L-S-M-L..., M and L are beside each other and S always faces L-M pair, allowing red+green brightness, red-green opponency, and yellow-blue opponency. L receptors work with three surrounding M receptors and three surrounding S receptors. M receptors work with three surrounding L receptors and three surrounding S receptors. S receptors work with six surrounding L+M receptor pairs, which are from three equilateral triangles, so each S has three surrounding L and three surrounding M receptors.

1.1.6.4. Retinal cells

Retina has 50 cell types.

Photoreceptor cells excite retinal neurons {bipolar cell}. There are ten bipolar-cell types. Peripheral-retina bipolar cells receive from more than one cone. Central-retina small bipolar cells {midget bipolar cell} receive from one cone. Bipolar cells send to inner plexiform layer to excite or inhibit ganglion cells (ON-center neurons and OFF-center neurons), which can be up to five neurons away. Large-dendrite-tree bipolar cells {diffuse bipolar cell} send to parasol ganglion cells.

Retinal cells {horizontal cell} can receive from receptor cells and inhibit bipolar cells.

Small retinal cells {amacrine cell} inhibit inner-plexiform-layer ganglion cells or excite transient ON-OFF-center neurons. There are 27 amacrine cell types.

1.1.6.5. Ganglion cells

Retinal neurons {ganglion cell} can receive from bipolar cells and send to thalamus lateral geniculate nucleus (LGN). Ganglion cells are similar to auditory nerve cells, Purkinje cells, olfactory bulb cells, olfactory cortex cells, and hippocampal cells.

Small central-retina ganglion cells {midget ganglion cell} receive from one midget bipolar cell. Most ganglion cells are midget ganglion cells.

Ganglion cells {parasol cell} {parasol ganglion cell} can receive from diffuse bipolar cells. Parasol cells are 10% of ganglion cells.

Ganglion X cells send to thalamus simple cells. X cells have large dendritic fields. X cells are more numerous in fovea.

Ganglion Y cells send to thalamus complex cells. Y cells have small dendritic fields. Y cells are more numerous in retinal periphery.

Ganglion W cells are small.

In early development, contralateral ganglion-cell optic-nerve fibers cross over to connect to optic tectum. In early development, optic-nerve fibers and brain regions have topographic maps. After maturation, axons can no longer alter connections.

1.2. Brain

Lateral geniculate nucleus, midbrain, and cortex process visual information.

Lateral geniculate nucleus (LGN) sends to visual-cortex hypercolumns.

At first-ventricle top, chordates have cells {lamellar body} with cilia and photoreceptors. In vertebrates, lamellar body evolved to make parietal eye and pineal gland.

1.3. Evolution

More than 500 million years ago, animal skin touch-receptor cells evolved photoreceptor protein for dim light, making light-sensitive rod cells. Rod-cell region sank into skin to make a dimple, so light can enter only from straight-ahead. Dimple became a narrow hole and, like pinholes, allowed image focusing on light-sensitive rod-cell region. Transparent skin covered narrow hole. Transparent-skin thickening created a lens, allowing better light gathering. Muscles controlled lens shape, allowing focusing at different distances.

500 million years ago, gene duplication evolved photoreceptor proteins for bright light, and cone cells evolved.

Pax-6 gene has homeobox and regulates head and eye formation.

Horseshoe crab (Limulus) eye {simple eye} can only detect light intensity, not direction. Input/output equation uses relation between Green function and covariance, because synaptic transmission is probabilistic.

2. Physiology

Perception (and imagination, dreaming, and memory-recall) process visual information to represent color, distance, and location. Vision analyzes light intensities and frequencies [Wallach, 1963] (it does not use electromagnetic-wave phase differences). Vision can detect colors, features, objects, spatial relations, groups, overlaps, scenes, and visual field. Vision can detect events and motions. Vision can detect brightness, contrast, texture, transparency, shadows, reflections, refractions, and diffractions. Vison can be focused, blurry, or hazy.

Vision is a synthetic sense. From each space direction/location, vision mixes colors and reduces frequency-intensity spectrum to one color and brightness.

Animal eyes are right and left, not above and below, to help align vertical direction.

Brain first extracts elementary perceptual units, contiguous lines, and non-accidental properties {early vision}. Brain then prepares to recognize objects and understand scenes {middle vision} {midlevel vision}. Brain then recognizes objects and understands scenes {high-level vision}.

Vision behaviors and uses determine vision phenomena {enactive perception} [Noë, 2002] [Noë, 2004] [O'Regan, 1992] [O'Regan and Noë, 2001]. Perhaps, the first vision was for direct sunlight, fire, lightning, or lightning bugs.

Vision can turn on and off ten times each second {cinematographic vision} [Sacks, 1970] [Sacks, 1973] [Sacks, 1984] [Sacks, 1995].

2.1. Receptor processing

Receptor cells detect visible light by absorbing light energy to depolarize cell membrane. Visual receptor cells hyperpolarize up to 30 mV from resting level [Dowling, 1987] [Enroth-Cugell and Robson, 1984] [Wandell, 1995]. Photoreceptors have maximum response at one frequency and lesser responses farther from that frequency. Visual-receptor cells find illumination logarithm.

Rod-shaped retinal cells detect large features and do not signal color. Rods have maximum sensitivity at 498 nm, blue-green. Just above cone threshold intensity {mesopic vision}, rods are more sensitive to short wavelengths, so blue colors are brighter but colorless.

Cone-shaped retinal cells detect color and visual details. Cone maximum wavelength sensitivities are at indigo 437 nm {short-wavelength cone}, green 534 nm {middle-wavelength cone}, and yellow-green 564 nm {long-wavelength cone}. When rods saturate, cones have approximately same sensitivity to blue and red. Cones do not detect pure or unmixed colors. Red light does not optimally excite one cone type but makes maximum excitation ratio between two cone types. Blue light excites short-wavelength cones and does not excite other cone types. Green light excites all cone types.

Brain can distinguish colors using light that only affects rod cells and long-wavelength cone cells.

Because different colors focus at different distances, to improve acuity, fovea has few short-wavelength cones [Curcio et al., 1991] [Roorda and Williams, 1999] [Williams et al., 1981] [Williams et al., 1991].

RPE cells maintain rods and cones by absorbing used molecules.

2.2. Retinal processing

Scene features land on retina at distances {eccentricity} {visual eccentricity} from fovea.

Ganglion cells separate information about shape, reflectance, illumination, and viewpoint.

Ganglion-cell spontaneous activity can be high or low [Dowling, 1987] [Enroth-Cugell and Robson, 1984] [Wandell, 1995]. For dark-adapted eye, absorbed photons supply one information bit. At higher luminance, 10,000 photons make one bit.

Retina neurons code for contrast, not brightness. Ganglion cells compare point brightness with average brightness. Nerve signal strength automatically adjusts to same value, whatever scene average brightness is. Most visual information comes from receptors near boundaries, which have large brightness or color contrasts.

ON-center midget bipolar cells increase output when light intensity increases in receptive-field center and/or decreases in receptive-field periphery. OFF-center midget bipolar cells increase output when light intensity decreases in receptive-field center and/or increases in receptive-field periphery.

Midget ganglion cells respond mostly to contrast.

Parasol ganglion cells respond mostly to change.

Ganglion X cells can make tonic and sustained signals, with slow conduction, to detect details and spatial orientation. Ganglion Y cells can make phasic and transient signals, with fast conduction, to detect stimulus size and temporal motion. Ganglion W cells are small, are direction sensitive, and have slow conduction speed.

ON-center ganglion cells respond when light intensity above background level falls on their receptive field. Light falling on field surround inhibits cell. Bipolar cells excite ON-center neurons. Four types of ON-center neuron depend on balance between cell excitation and inhibition. One has high firing rate at onset and zero rate at offset. One has high rate at onset, then zero, then high, and then zero. One has high rate at onset, goes to zero, and then rises to constant level. One has high rate at onset and then goes to zero.

OFF-center ganglion cells increase output when light intensity decreases in receptive-field center. Light falling on field surround excites cell. Bipolar cells excite OFF-center neurons.

ON-OFF-center ganglion cells for motion use ON-center-neuron time derivatives to find movement position and direction. Amacrine cells excite transient ON-OFF-center neurons.

Amacrine cells inhibit inner-plexiform-layer ganglion cells, using antitransmitter to block pathways.

2.3. Brain processing

Lateral-geniculate-nucleus parvocellular neurons measure colors {chromatic channel} {spectrally opponent channel}. Lateral-geniculate-nucleus magnocellular neurons measure luminance {luminance channel} {achromatic channel} {spectrally non-opponent channel}.

Brain sends little feedback to retina [Brooke et al., 1965] [Spinelli et al., 1965].

2.3.1. Occipital lobe

Neurons {color-opponent cell} can detect output differences from different cone cells for same space direction. Cells {double-opponent neuron} can have both ON-center and OFF-center circular fields and compare colors.

Cortical-neuron sets {spatial frequency channel} can detect different spatial-frequency ranges and so detect different object sizes.

One thousand cortical cells collectively {cardinal cell} code for one perception type.

Brain processes object recognition and color from area V1, to area V2, to area V4, to inferotemporal cortex. Cortical area V1, V2, and V3 damage impairs shape perception and pattern recognition, leaving only flux perception. Lateral inhibition and spreading excitation help find color categories and space surfaces.

Area V2 detects contour orientation, regardless of luminance.

Area-V4 neurons {color difference neuron} can detect adjacent and surrounding color differences, by relative intensities at different wavelengths. Area 4 detects contour orientation, regardless of luminance, and so detects curved boundaries.

Brain processes locations and actions in a separate faster pathway. Location perception is before color perception.

Color perception is before orientation perception, and is 80 ms before motion perception. If people must choose, they associate current color with motion 100 ms before. Brain associates two colors or motions before associating color and motion.

2.3.2. Temporal lobe

Middle temporal-lobe area V5 detects pattern directions and motion gradients. Dorsal medial superior temporal lobe detects heading.

Inferotemporal lobe (IT) detects shape parts. IT and CIP detect curvature and orientation.

2.3.3. Parietal lobe

Posterior parietal and pre-motor cortex plan and command voluntary eye movements [Bridgeman et al., 1979] [Bridgeman et al., 1981] [Goodale et al., 1986].

Stimulating superior-colliculus neurons can cause angle-specific eye rotation. Stimulating frontal-eye-field or other superior-colliculus neurons makes eyes move to specific locations, no matter from where eye started.

2.4. Intensity

Photons have emissions, absorptions, vibrations, reflections, and transmissions. Long-wavelength photons have less energy, and short-wavelength photons have more energy, because photon energy relates directly to frequency.

Color varies in energy flow per unit area {intensity}. Vision can detect very low intensity. People can see over ten-thousand-fold light intensity range. People can perceive one-percent intensity differences. Vision is painful at high intensity.

Eyes blinded by bright light recover in 30 minutes, as eye chemicals become unbleached.

After people view unchanging images for two or three seconds, image fades and becomes dark gray or black. If object contains sharp boundaries between highly contrasting areas, object reappears intermittently.

If incident light changes spectra, people can briefly see macula image {Maxwell spot}.

2.4.1. Luminance

Light sources {illuminant} shine light on observed surfaces.

Light {luminous flux} can shine in a direction with a spectrum of wavelengths. Leaving, arriving, or transmitted luminous flux divided by surface area {luminance} is a constant times sum over frequencies of spectral radiant energy times long-wavelength-cone and short-wavelength-cone spectral-sensitivity function [Autrum, 1979] [Segall et al., 1966]. Luminance relates to brightness.

Lateral-geniculate-nucleus magnocellular neurons measure luminance {luminance channel} {achromatic channel} {spectrally non-opponent channel}. (Lateral-geniculate-nucleus parvocellular neurons measure colors {chromatic channel} {spectrally opponent channel}.)

Light power (radiance) and energy differ at different frequencies {spectral power distribution}, typically in 31 ranges 10 nm wide between 400 nm and 700 nm. Light {radiant flux} can emit or reflect with a spectrum of wavelengths. Radiant flux divided by surface area canbe in a direction {radiance} or spread out {irradiance}.

2.4.2. Brightness

Phenomenal brightness {brightness} {luminosity} relates to logarithm of total stimulus-intensity energy flux from all wavelengths. Surfaces that emit more lumens are brighter. On Munsell scale, brightness increases by 1.5 units if lumens double. Surfaces that reflect different spectra, but emit same number of lumens, are equally bright. Brightness is relative and depends on ambient light. Brightness depends on mental state.

People have different abilities to detect color radiance. Typical people {Standard Observer} have maximum sensitivity at 555 nm and see luminance according to standard radiance weightings at different wavelengths. Brightness varies with luminance logarithm.

Color perception depends on hue, saturation, and brightness. Mostly hue and saturation {chromaticity} make colors. Brightness does not affect chromaticity much [Kandel et al., 1991] [Thompson, 1995].

Assume primary colors can have brightness 0 to 100. If red is 100, green is 0, and blue is 0, hue is bright red. If red is 50, green is 0, and blue is 0, hue is dark red. If red is 100, green is 100, and blue is 0, hue is bright yellow. If red is 50, green is 50, and blue is 0, hue is dark yellow. If red is 100, green is 50, and blue is 0, hue is bright orange. If red is 50, green is 25, and blue is 0, hue is dark orange.

At constant luminance, brightness depends on both saturation and hue {Helmholtz-Kohlrausch effect}. If hue is constant, brightness increases with saturation. If saturation is constant, brightness changes with hue.

For spectral colors, brightness is logarithmic, not linear, with reflectivity.

If stimulus lasts less than 0.1 second, brightness is product of intensity and duration {Bloch's law} {Bloch law}.

Light colors change less, and dark colors change more, as source brightness increases. Light colors change less, and dark colors change more, as color saturation decreases.

Not stimulating long-wavelength or middle-wavelength receptors reduces brightness. For example, extreme purples are less bright than other colors.

If light has constant intensity for less than 100 ms, brain perceives it as becoming less bright. If light has constant intensity for 100 ms to 300 ms, brain perceives it as becoming brighter. If light has constant intensity for longer than 300 ms, brain perceives it as maintaining same brightness.

Brightness depends on eye adaptation state. Parallel pathways calculate brightness. One pathway adapts to constant-intensity stimuli, and the other does not adapt. If two same-intensity flashes start at same time, briefer flash looks dimmer than longer flash. If two same-intensity flashes end at same time, briefer flash looks brighter than longer flash {temporal context effect} (Sejnowsky). Visual system uses visual-stimulus timing and spatial context to calculate brightness.

Good brightness control increases all intensities by same amount. Consciousness cannot control brightness directly.

Note: Television Brightness control sets "picture" level by increasing input-signal multiple {gain}. If gain is too low, high-input signals have low intensity and many low-input signals are same black. If gain is too high, low-input signals have high intensity and many high-input signals are same white. Television Brightness control increases ratio between black and white and so really changes contrast.

2.4.3. Color lightness

Fraction of incident light transmitted or reflected diffusely {lightness} {luminance factor} sums the three primary-color (red, green, and blue) brightnesses. Assume each color can have brightness 0 to 100. For example, if red is 100, green is 100, and blue is 100, lightness is maximum brightness. If red is 100, green is 100, and blue is 50, lightness is 83% maximum brightness. If red is 100, green is 50, and blue is 50, lightness is 67% maximum brightness. If red is 67, green is 17, and blue is 17, lightness is 33% maximum brightness. If red is 17, green is 17, and blue is 17, lightness is 17% maximum brightness.

2.4.4. Contrast

Detected light has difference between lowest and highest intensity {contrast}.

Vision can detect smallest intensity difference {contrast threshold} between light and dark surface area. Larger objects have smaller contrast thresholds. Stimulus-size spatial frequency determines contrast-threshold reciprocal {contrast sensitivity function} (CSF). Contrast-threshold reciprocal is large when contrast threshold is small.

Visual system increases brightness contrast across edges {edge enhancement}, making lighter side lighter and darker side darker {Mach band}.

Good contrast control sets black to zero intensity while decreasing or increasing maximum intensity. Consciousness cannot control contrast directly.

Note: Television Contrast control sets "black level" by shifting lowest intensity to shift intensity scale. It adjusts input signal to make zero intensity. If input is too low, lower input signals all result in zero intensity. If input is too high, lowest input signal results in greater than zero intensity. Television Contrast control changes all intensities by same amount and so really changes brightness.

2.4.5. Dark Adaptation

Rods and cones {duplex vision} operate in different light conditions.

Vision has systems {photopic system} for daylight conditions. Vision has systems {scotopic system} for dark or nighttime conditions.

Seeing at dusk {mesopic vision} {twilight vision} is more difficult and dangerous.

Sensitivity improves in dim light when using both eyes.

In low-light conditions, people see three-degrees-of-arc circular regions, alternating randomly between black and white several times each second {variable resolution}. If eyes move, pattern moves. In slightly lighter conditions, people see one-degree-of-arc circular regions, alternating randomly between dark gray and light gray, several times each second. In light conditions, people see colors, with no flashing circles. Flicker rate varies with activity. If you relax, flicker rate is 4 to 20 Hz. If flicker rate becomes more than 25 Hz, you cannot see flicker. Flicker shows that sense qualities have elements. Variable-resolution size reflects sense-field dynamic building. Perhaps, fewer receptor numbers can respond to lower light levels. Perhaps, intensity modulates natural oscillation. Perhaps, rods have competitive inhibition and excitation [Hardin, 1988] [Hurvich, 1981].

In dim light, without focus on anything, black, gray, and white blobs, smaller in brighter light and larger in dimmer light, flicker on surfaces. In darkness, people see large-size regions slowly alternate between black and white. Brightest blobs are up to ten times brighter than background.

2.5. Hue

Spectral colors {hue} depend on light wavelength and frequency. People can distinguish 160 hues, over light of wavelengths 400 nm to 700 nm.

Lateral-geniculate-nucleus parvocellular neurons measure colors {chromatic channel} {spectrally opponent channel}. (Lateral-geniculate-nucleus magnocellular neurons measure luminance {luminance channel} {achromatic channel} {spectrally non-opponent channel}.)

If luminance is enough to stimulate cones, hue changes as luminance changes {Bezold-Brücke phenomenon} {Bezold-Brücke effect}.

Hue depends on saturation {Abney effect}.

2.5.1. Color frequencies and wavelengths

Color relates directly to electromagnetic wave frequency {color frequency} and intensity. Frequency is light speed, 3.02 x 10^8 m/s, divided by wavelength.

Light waves that humans can see have frequencies between 420 and 790 million million cycles per second, 420 and 790 teraHertz or THz. Vision can detect about one octave of light frequencies:

- Red light has frequency range 420 THz to 480 THz.
- Orange light has frequency range 480 THz to 510 THz.
- Yellow light has frequency range 510 THz to 540 THz.
- Green light has frequency range 540 THz to 600 THz.
- Blue light has frequency range 600 THz to 690 THz.
- Indigo or ultramarine light has frequency range 690 THz to 715 THz.
- Purple light has frequency range 715 THz to 790 THz.

Colors differ in frequency range and in range compared to average wavelength. Range is greater and higher percentage for longer wavelengths:

- Reds have widest range. Red goes from infrared 720 nm to red-orange 625 nm = 95 nm. 95 nm/683 nm = 14%. Reds have more spread and less definition.
- Greens have narrower range. Green goes from chartreuse 560 nm to cyan 500 nm = 60 nm. 60 nm/543 nm = 11%.
- Blues have narrowest range. Blue goes from cyan 480 nm to indigo or ultramarine 440 nm = 40 nm. 40 nm/463 nm = 8%. Blues have less spread and more definition.

Spectral colors have wavelength ranges:

- red = 720 nm to 625 nm
- orange = 625 nm to 590 nm
- yellow = 590 nm to 575 nm
- chartreuse = 575 nm to 555 nm
- green = 555 nm to 520 nm
- cyan = 520 nm to 480 nm
- blue = 480 nm to 440 nm
- indigo or ultramarine = 440 nm to 420 nm
- purple = 420 nm to 380 nm

Spectral colors have maximum purity at specific frequencies:

- red = 436 THz, orange = 497 THz
- yellow = 518 THz
- chartreuse = 539 THz
- green = 556 THz
- cyan = 604 THz
- blue = 652 THz
- indigo or ultramarine = 694 THz

- purple = 740 THz

Spectral colors have maximum purity at specific wavelengths:

- red = 683 nm
- orange = 608 nm
- yellow = 583 nm
- chartreuse = 560 nm
- green = 543 nm
- cyan = 500 nm
- blue = 463 nm
- indigo or ultramarine = 435 nm
- purple = 408 nm
- Magenta is not spectral color but is red-purple, so assume wavelength is 730 nm or 375 nm.

Different colors have different sensiitivies:

- Blue is most sensitive at 482 nm, where it just turned blue from greenish-blue.
- Green is most sensitive at 506 nm, at middle. Yellow is most sensitive at 568 nm, just after greenish-yellow.
- Red is most sensitive at 680 nm, at middle red.

Colors are symmetric around middle of long-wavelength and middle-wavelength receptor maximum-sensitivity wavelengths 550 nm and 530 nm. Wavelength 543 nm has green color. Chartreuse, yellow, orange, and red are on one side. Cyan, blue, indigo or ultramarine, and purple are on other side:

- Yellow is 583 - 543 = 40 nm from middle.
- Orange is 608 - 543 = 65 nm from middle.
- Red is 683 - 543 = 140 nm from middle.
- Blue is 543 - 463 = 80 nm from middle.
- Indigo or ultramarine is 543 - 435 = 108 nm from middle.
- Purple is 543 - 408 = 135 nm from middle.

2.5.2. Spectral colors

People can see colors {spectral color} from illumination sources:

- Purples are 380 to 435 nm, with middle 408 nm and range 55 nm.
- Blues are 435 to 500 nm, with middle 463 nm and range 65 nm.
- Cyans are 500 to 520 nm, with middle 510 nm and range 20 nm.
- Greens are 520 to 565 nm, with middle 543 nm and range 45 nm.
- Yellows are 565 to 590 nm, with middle 583 nm and range 35 nm.
- Oranges are 590 to 625 nm, with middle 608 nm and range 35 nm.
- Reds are 625 to 740 nm, with middle 683 nm and range 115 nm.

Spectral colors start at short-wavelength purplish-blue:

- Purplish-blues are 400 to 450 nm, with middle 425 nm.
- Blues are 450 to 482 nm, with middle 465.
- Greenish-blues are 482 to 487 nm, with middle 485 nm.
- Blue-greens are 487 to 493 nm, with middle 490 nm.
- Bluish-greens are 493 to 498 nm, with middle 495 nm.
- Greens are 498 to 530 nm, with middle 510 nm.
- Yellowish-greens are 530 to 558 nm, with middle 550 nm.
- Yellow-greens are 558 to 568 nm, with middle 560 nm.
- Greenish-yellows are 568 to 572 nm, with middle 570 nm.
- Yellows are 572 to 578 nm, with middle 575 nm.
- Yellowish-oranges are 578 to 585, with middle 580 nm.
- Oranges are 585 to 595 nm, with middle 590 nm.
- Reddish-oranges and orange-pinks are 595 to 625 nm, with middle 610 nm.
- Reds and pinks are 625 to 740 nm, with middle 640 nm.
- Spectral colors end at long-wavelength purplish-red.

Blue, red, yellow, and green describe pure colors {unique hue}. Unique red occurs only at low brightness, because more brightness adds yellow. Other colors mix unique hues. For example, orange is reddish yellow or yellowish red, and purples are reddish blue or bluish red.

2.5.3. Color differences

People can distinguish colors differing by approximately 2 nm of wavelength. People can detect smaller wavelength differences between 500 nm and 600 nm than above 600 nm or below 500 nm, because two cones have maximum sensitivities within that range.

Similar colors have similar average light-wave frequencies. Colors with more dissimilar average light-wave frequencies are more different.

2.5.4. Color opponencies

Cone outputs can subtract and add {opponency} {color opponent process} {opponent color theory} {tetrachromatic theory}.

Middle-wavelength cone output subtracts from long-wavelength cone output, L - M, to detect blue, green, yellow, orange, pink, and red. Maximum is at red, and minimum is at blue. Hue calculation is in lateral geniculate nucleus, using neurons with center and surround. Center detects long-wavelengths, and surround detects medium-wavelengths [Hardin, 1988] [Hurvich, 1981] [Katz, 1911] [Lee and Valberg, 1991].

Short-wavelength cone output subtracts from long-wavelength plus middle-wavelength cone output, (L + M) - S, to detect purple, indigo or ultramarine, blue, cyan, green, yellow, and red. Maximum is at chartreuse, minimum is at purple, and red is another minimu is at red. Saturation calculation is in lateral geniculate nucleus, using neurons with center and surround. Luminance output goes to center, and surround detects short-wavelengths [Hardin, 1988] [Hurvich, 1981] [Katz, 1911] [Lee and Valberg, 1991].

Long-wavelength and middle-wavelength cones add to detect luminance brightness: L + M. Short-wavelength cones are few. Luminance calculation is in lateral geniculate nucleus, using neurons with center and surround. Center detects long-wavelengths, and surround detects negative of medium-wavelengths [Hardin, 1988] [Hurvich, 1981] [Katz, 1911] [Lee and Valberg, 1991]. Brain uses luminance to find edges and motions.

Each opponent system has a specific relative response for each wavelength {chromatic-response curve}:

- The brightness-darkness system has maximum response at 560 nm and is symmetric between 500 nm and 650 nm.
- The red-green system has maximum response at 610 nm and minimum response at 530 nm and is symmetric between 590 nm and 630 nm and between 490 nm and 560 nm.
- The blue-yellow system has maximum response at 540 nm and minimum response at 430 nm and is symmetric between 520 nm and 560 nm and between 410 nm and 450 nm.

Different colors affect cones differently:

- Red affects long-wavelength some. Orange affects long-wavelength well. Yellow affects long-wavelength most. Green affects middle-wavelength most. Blue affects short-wavelength most.
- Indigo or ultramarine, because it has blue and some red, affects long-wavelength and short-wavelength. Purple, because it has blue and more red, affects long-wavelength more and short-wavelength less. Magenta, because it has half red and half blue, affects long-wavelength and short-wavelength equally.
- White, gray, and black affect long-wavelength receptor and middle-wavelength receptor equally, and long-wavelength receptor plus middle-wavelength receptor and short-wavelength receptor equally. Complementary colors add to make white, gray, or black.

Different colors affect opponencies differently:

- For red, L - M is maximum, and L + M - S is maximum.
- For orange, L - M is positive, and L + M - S is maximum.
- For yellow, L - M is half, and L + M - S is maximum.
- For green, L - M is zero, and L + M - S is zero.
- For blue, L - M is minimum, and L + M - S is minimum.
- For magenta, L - M is half, and L + M - S is half.
- Adding white, to make more unsaturation, decreases L - M values and increases L + M - S values.

When positive and negative contributions are equal, opponent-color processes can give no signal {neutral point}:

- For the L - M opponent process, red and cyan are complementary colors and mix to make white.
- For the L + M - S opponent process, blue and yellow are complementary colors and mix to make white.
- The L + M sense process has no neutral point.

People can see colors {non-spectral hue} that have no single wavelength but require two wavelengths. For example, mixing red and blue makes magenta and other reddish purples. Such a mixture stimulates short-wavelength cones and long-wavelength cones but not middle-wavelength cones.

Theoretically, for people to see color, the three primate cone receptors must be maximally sensitive at blue, green, and yellow-green, which requires opponency to determine colors and has color complementarity. The three cones do not have maximum sensitivity at red, green, and blue, because each sensor is then for one main color, and system has no complementary colors. Such a system has no opponency, because those opponencies have ambiguous ratios and ambiguous colors.

2.5.5. Univariance

The same hue can result from light of one wavelength or light mixtures with different wavelengths. Hue is the weighted average of light wavelengths. Different wavelength and intensity combinations can result in same output. Photoreceptors can have the same output for an infinite number of stimulus frequency-intensity combinations {univariance problem} {problem of univariance} {univariance principle} {principle of univariance}.

Color-vision systems have one or more receptor types, each able to absorb a percentage of quanta at each wavelength {wavelength mixture space}. Photon absorption causes one photoreceptor molecule to isomerize. Isomerization reactions are the same for all stimulus frequencies and intensities. Different photon wavelengths have different absorption probabilities, from 0% to 10%. Higher-intensity low-probability wavelengths can make same total absorption as lower-intensity high-probability wavelengths. For example, if frequency A has probability 1% and intensity 2, and frequency B has probability 2% and intensity 1, total absorption is same.

2.5.6. Color spaces

Three-dimensional mathematical spaces {color space} give colors coordinates.

Color space {chromaticity diagram} {CIE Chromaticity Diagram} can use luminance Y and two coordinates, x and y, related to hue and saturation. CIE system uses spectral power distribution (SPD) of light emitted from surfaces. CIE system can use any three primary colors, not just red, green, and blue.

Retina has three cone types, each with maximum-output stimulus frequency {tristimulus values}, established by eye sensitivity measurements. Using tristimulus values allows factoring out luminance brightness to establish luminance coordinate. Factoring out luminance leaves two chromaticity color coordinates. Color space can use tristimulus values.

Color space can use chromaticity coordinates to define a border of an upside-down U-shaped space, giving all maximum-saturation hues from 400 to 700 nm. Along the flat bottom border are purples. Plane middle regions represent decreasing saturation from edges to middle, with completely unsaturated white (because already white) in middle. For example, between middle white and border reds and purples are pinks. Central point is where x and y equal 1/3. From border to central white, regions have same color with less saturation [Hardin, 1988].

Color space {Munsell color space} can use color samples spaced by equal differences. Hue is on color-circle circumference, with 100 equal hue intervals. Saturation {chroma} {chrominance} is along color-circle radius, with 10 to 18 equal intervals, for different hues. Brightness {light value} is along perpendicular above color circle, with black at 0 units and white at 10 units. Magenta is between red and purple. In Munsell system, red and cyan are on same diameter, yellow and blue are on another diameter, and green and magenta are on a diameter [Hardin, 1988].

Color space {Ostwald color space} can use standard samples and depend on reflectance. Colors have three coordinates: percentage of total lumens for main wavelength C, white W, and black B. Wavelength is hue. For given wavelength, higher C gives greater purity, and higher W with lower B gives higher luminance [Hardin, 1988].

Color space {Swedish Natural Color Order System} (NCS) can depend on how primary colors and other colors mix [Hardin, 1988].

2.5.7. Color wheels

Circular color scales {color wheel} can show sequence from red to magenta.

Colors on circle circumference can show correct color mixing. Two-color mixtures have color halfway between the colors. Complementary colors are opposite. Three complementary colors are 120 degrees apart. Red is at left, blue is 120 degrees to left, and green is 120 degrees to right. Yellow is halfway between red and green. Cyan is halfway between blue and green. Magenta is halfway between red and blue. Orange is between yellow and red. Chartreuse is between yellow and green. Indigo or ultramarine is between blue and purple. Purple is between indigo or ultramarine and magenta. Non-spectral colors are in quarter-circle from purple to red. Indigo or ultramarine, green, and yellow-green positions make a half-circle.

For subtractive colors, shift bluer colors one position: red opposite green, vermilion opposite cyan, orange opposite blue, yellow opposite indigo, and chartreuse opposite purple. Color subtraction makes darker colors, which are bluer, because short-wavelength receptor has higher weighting than other two receptors. It affects reds and oranges little, greens some, and blues most. Blues and greens shift toward red to add less blue, so complementary colors make black rather than blue-black.

A color wheel describes quantum-chromodynamics quark color-charge complex-number vectors and additive colors. On complex-plane unit circle, red coordinates are (+1, 0*i). Green coordinates are (-1/2, -(3^(0.5))*i/2). Blue coordinates are (-1/2, +(3^(0.5))*i/2). Yellow coordinates are (+1/2, -(3^(0.5))*i/2). Cyan coordinates are (-1, 0*i). Magenta coordinates are (+1/2, +(3^(0.5))*i/2). To find color mixtures, add vectors. Two quarks add to make muons, which have no color and whose resultant vector is zero, like complementary colors. Three quarks add to make protons and neutrons, which have no color and whose resultant vector is zero, like white. Color mixtures that result in non-zero vectors have colors and are not physical.

A color wheel can separate all colors equally. Divide color circle into 20 parts with 18 degrees each. Red = 0, orange = 2, yellow = 4, chartreuse = 6, green = 8, cyan = 10, blue = 12, indigo or ultramarine = 14, purple = 16, and magenta = 18. Crimson = 19, cyan-blue turquoise at 11, cyan-green at 9, yellow-orange = 3, and red-orange vermilion = 1. Primary colors are at 0, 8, and 12. Secondary colors are at 4, 10, and 18. Tertiary colors are at 2, 6, and 14/16. Complementary colors are opposite.

A color wheel can set magenta = 0 and green = 1. Red = 0.33, and blue = 0.33. Yellow = 0.67, and cyan = 0.67. Complementary colors add to 1.

Blue, green, yellow, and red can make a square. Green is halfway between blue and yellow. Yellow is halfway between green and red. Blue is halfway between green and red in other direction. Red is halfway between yellow and blue in other direction. Complementary pigments are opposite. Adding magenta, cyan, chartreuse, and orange makes eight points, like tones of an octave but separated by equal intervals, which can be harmonic ratios: 2/1, 3/2, 4/3, and 5/4.

Color wheels have no black or white, because they have no color and are only about brightness. Adding a black/gray/white dimension to a color wheel makes a color cylinder, on which unsaturated colors are pastels or dark colors.

2.5.8. Mixing Colors

Colors can mix {color mixture}. Colors are not symmetric, so colors have unique relations. Colors cannot substitute. Colors relate in only one consistent and complete way, and can mix in only one consistent and complete way.

Similar colors mix to make the intermediate color. Two colors mix to make the intermediate color. For example, red and orange make red-orange vermilion.

Colors mix with white to make pastel colors.

Red, green, and blue are the primary additive colors. Colors from light sources add {additive color mixture}. Primary additive-color mixtures make secondary additive colors: yellow from red and green, magenta from red and blue, and cyan from green and blue. Mixing primary and secondary additive colors makes tertiary additive colors: orange from red and yellow, purple from blue and magenta, and chartreuse from yellow and green.

No additive spectral-color mixture can make blue or red. Magenta and orange cannot make red, because magenta has blue, orange has yellow and green, and red has no blue or green. Indigo and cyan cannot make blue, because indigo has red and cyan has green, and blue has no green or red.

Red, yellow, and blue, or magenta, yellow, and cyan, are the primary subtractive colors. For subtractive colors, combining three pure color pigments {primary color}, such as red, yellow, and blue, can make most other colors. Mixing primary-color pigments makes magenta from red and blue, green from blue and yellow, and orange from red and yellow {secondary color}. Mixing primary-color and secondary-color pigment makes chartreuse from yellow and green, cyan from blue and green, purple from blue and magenta, red-magenta, red-orange, and yellow-orange {tertiary color} {intermediate color}. Primary colors are not unique. Besides red, yellow, and blue, other triples can make most colors.

Colors from pigmented surfaces have colors from source illumination minus colors absorbed by pigments {subtractive color mixture}. Colors from pigment reflections cannot add to make red or to make blue. Blue and yellow pigments reflect green, because both reflect some green, and sum of greens is more than reflected blue or yellow. Red and yellow pigments reflect orange, because each reflects some orange, and sum of oranges is more than reflected red or yellow. For subtractive colors, mixing cannot make red, blue, or yellow. Magenta and orange cannot make red, because magenta has blue, orange has yellow and green, and red has no blue or green. Indigo and cyan cannot make blue, because indigo has red and cyan has green, and blue has no red or green. Chartreuse and orange cannot make yellow, because chartreuse has green and some indigo, orange has red and some indigo, and yellow has no indigo.

A wheel with black and white areas, rotated five Hz to ten Hz to give flicker rate below fusion frequency, in strong light, can produce intense colors {Benham's top} {Benham top} {Benham disk}, because color results from different color-receptor-system time-constants.

2.5.8.1. Complementary colors

Two colors {complementary color} can add to make white. Complementary colors can be primary, secondary, or tertiary colors.

Colors with equal amounts of red, green, and blue make white. Red and cyan, yellow and blue, or green and magenta make white. Equal red, blue, and green contributions make white light.

Colors that mix to make equal amounts of red, yellow, and blue make black. Orange and blue, yellow and indigo/purple, or green and red make black. Equal magenta, yellow, and cyan contributions make black.

2.5.8.2. Grassman laws

Grassmann described color-mixing laws {Grassmann's laws} {Grassmann laws}. Grassmann's laws are vector additions and multiplications in wavelength mixture space.

If two pairs of wavelengths at specific intensities result in same color, adding the pairs gives same color: if C1 + C2 = x and C3 + C4 = x, then C1 + C2 + C3 + C4 = x. For example, if blue-and-yellow pair makes green, and two greens together make same green, adding pairs makes same green.

If pair of wavelengths at specific intensities makes color, adding same wavelength and intensity to each makes same color as adding it to the pair. If C1 + C2 = x and C3 = y, then (C1 + C3) + (C2 + C3) = (C1 + C2) + C3 = z. For example, if blue-and-yellow pair makes green, adding red to blue and to yellow makes same color as adding red to the pair.

If pair of wavelengths at specific intensities makes color, changing both intensities equally makes same color as changing pair intensity. If C1 + C2 = x, then n*C1 + n*C2 = n*(C1 + C2) = w. For example, if blue-and-yellow pair makes green, increasing both color intensities by same amount makes same green, only brighter.

2.5.9. Adjacent colors and contrast

Adjacent colors enhance their contrast by adding each color's complementary color to the other color. Adjacent black and white also have enhanced contrast.

If two different colors are adjacent, each color adds its complementary color to the other {color contrast}. If bright color is beside dark color, contrast increases. If white and black areas are adjacent, they add opposite color to each other. If another color overlays background color, brighter color dominates. If brighter color is in background, it shines through overlay. If darker color is in background, overlay hides it.

Two adjacent different-colored objects have enhanced color differences {successive contrast} {simultaneous contrast}.

2.6. Saturation

Pure saturated color {saturation} {purity} has no white, gray, or black. White, gray, and black have zero purity. Spectral colors can have different white, gray, or black percentages (unsaturation).

The purest most-saturated color has light with one wavelength. Saturated color pigments reflect light with narrow wavelength range. Unsaturated pigments reflect light with wide wavelength range.

All spectral colors can mix with white. White has no saturation. Monochromatic yellows have largest saturation range (as in Munsell color system), change least as saturation changes, and look least saturated at all saturation levels. Monochromatic greens have second-largest saturation range, change second-least as saturation changes, and look second-least saturated at all saturation levels. Monochromatic reds have average saturation range, change third-least as saturation changes, and look third-least saturated at all saturation levels. Monochromatic blues have smallest saturation range, change most as saturation changes, and look fourth-least saturated (least white) at all saturation levels. Black is darkest and looks most saturated.

Saturated pigments mixed with black make dark colors, like ochre. Saturated pigments mixed with white make light pastel colors, like pink.

If all three primary colors (red, green, and blue) are present, color has unsaturation. Unsaturation percentage is percent of maximum brightness of least-bright primary color. Assume colors can have brightness 0 to 100. If red is 100, green is 100, and blue is 100, saturation is 0%. If red is 50, green is 50, and blue is 50, saturation is 0%. If red is 0, green is 0, and blue is 0, saturation is 0%. If red is 100, green is 100, and blue is 50, yellow saturation is 50%. If red is 50, green is 50, and blue is 25, gray yellow saturation is 50%. If red is 100, green is 50, and blue is 50, red (pink) saturation is 50%. If red is 50, green is 25, and blue is 25, grey pink saturation is 50%. If red is 75, green is 50, and blue is 25, orange saturation is 50%.

Saturation increases as luminance increases {Hunt effect}.

2.7. Contours

Boundaries {contour} have brightness differences and are the most-important visual perception. Contours belong to objects, not background.

Light and shade have contours. Light is typically above objects. Light typically falls on nearer objects. Shadows are typically below objects. Shade typically falls on farther objects.

Mind extrapolates or interpolates contour segments to make object contours {completion}.

Perception extends actual lines to make imaginary figure edges {subjective contour}. Subjective contours affect depth perception.

When looking only at object-boundary part, even young children see complete figures. Children see completed outline, though they know it is not actually there.

If background contours surround figure, figure discrimination and recognition fail.

Two line segments can belong to same contour {relatability}.

Curved surfaces have perpendicular curved long and short axes. In solid objects, short axis is object depth axis and indicates surface orientation. Curved surfaces have dark edge in middle, where light and dark sides meet.

2.8. Filling-in

If limited or noisy stimuli come from space region, perception completes region boundaries and surface textures {filling-in} {closure}, using neighboring boundaries and surface textures.

Filling-in always happens, so people never see regions with missing information. If region has no information, people do not notice region, only scene.

Brain fills in using plausible guesses from surroundings and interpolation from periphery. For large damaged visual-cortex region, filling-in starts at edges and goes inward toward center, taking several seconds to finish [Churchland and Ramachandran, 1993] [Dahlbom, 1993] [Kamitani and Shimojo, 1999] [Pessoa and DeWeerd, 2003] [Pessoa et al., 1998] [Poggio et al., 1985] [Ramachandran, 1992] [Ramachandran and Gregory, 1991].

Filling-in uses whole brain, especially innate and learned memories, as various neuron assemblies form and dissolve and excite and inhibit.

Because local neural processing makes incomplete and approximate representations, typically with ambiguities and contradictions, global information uses marked and indexed features to build complete and consistent perception. Brain uses global information when local region has low receptor density, such as retina blindspot or damaged cells. Global information aids perception during blinking and eye movements.

Brain fills in using line completion, motion continuation, and color spreading. Brain fills areas and completes half-hidden object shapes. Blindspot filling-in maintains lines and edges {completion}, preserves motion using area MT, and keeps color using area V4.

Surfaces have periodic structure and spatial frequency. Surface texture can expand to help filling in. Blindspot filling-in continues background texture using area V3.

Surfaces recruit neighboring similar surfaces to expand homogeneous regions by wave entrainment. Contours align by wave entrainment.

Lateral inhibition distinguishes and sharpens boundaries. Surfaces use constraint satisfaction to optimize edges and regions.

Brain perceives occluded object as whole-object figure partially hidden behind intervening-object ground {conceptual filling-in}, not as separate, unidentified shape beside intervening object.

2.9. Depth Perception

Brain can find depth and distance {depth perception} {distance perception} in scenes, paintings, and photographs.

People learn depth perception and can lose depth-perception abilities.

In the dark, objects appear closer.

2.9.1. Stereoscopy

Using both eyes can make depth and three dimensions appear {stereoscopic depth} {stereoscopy} {stereopsis}. Stereopsis aids random shape perception. Stereoscopic data analysis is independent of other visual analyses. Monocular depth cues can cancel stereoscopic depth. Stereoscopy does not allow highly unlikely depth reversals or unlikely depths. Scene features land on one retina point {uniqueness constraint}, so brain stereopsis can match right-retina and left-retina scene points.

Binocular depth perception requires only ground plane and eye point to establish coordinate system. Perhaps, sensations aid depth perception by building geometric images [Poggio and Poggio, 1984].

Scenes land on right and left eye with same geometric shape, so feature distances and orientations are the same {corresponding retinal points}.

Both eyes can turn outward {divergence}, away from each other, as objects get farther. If divergence is successful, there is no retinal disparity.

For far objects, with very small retinal disparity, shadows can still have perceptibly different angles {shadow stereopsis} [Puerta, 1989], so larger angle differences are nearer, and smaller differences are farther.

If eye visual fields overlap, the two scenes differ by a linear displacement, due to different sight-line angles. For a visual feature, displacement is the triangle base, which has angles at each end between the displacement line and sight-line, allowing triangulation to find distance. At farther distances, displacement is smaller and angle differences from 90 degrees are smaller, so distance information is imprecise. Inference includes objects at edges of retinal overlap in stereo views.

2.9.2. Retinal size

People have previous experience with objects and their size, so larger retinal size is closer, and smaller retinal size is farther. If two objects have the same shape and are judged to be the same, object with larger retinal size is closer.

Brain expands more distant objects in proportion to the more contracted retinal-image size, making apparent size increase with increasing distance {size-constancy scaling} {Emmert's law} {Emmert law}. Brain determines size-constancy scaling by eye convergence, geometric perspective, texture gradients, and image sharpness. Texture gradients decrease in size with distance. Image sharpness decreases with distance.

Closer objects have higher edge contrast, more edge sharpness, position nearer scene bottom, larger size, overlap on top, and transparency. Higher edge contrast is most important. More edge sharpness is next most important. Position nearer scene bottom is more important for known eye-level. Transparency is least important. Nearer objects are redder.

Farther objects have smaller retinal size; are closer to horizon (if below horizon, they are higher than nearer objects); have lower contrast; are hazier, blurrier, and fuzzier with less texture details; and are bluer or greener. Nearer objects overlap farther objects and cast shadows on farther objects.

2.9.3. Distance calculation

ON-center-neuron, OFF-center-neuron, and orientation-column intensities build two-dimensional line arrays, then two-and-one-half-dimensional contour arrays, and then three-dimensional surfaces and texture arrays [Marr, 1982].

Brain derives three-dimensional images from two-dimensional ones by assigning convexity and concavity to lines and vertices and making convexities and concavities consistent.

Adjacent points not at edges are on same surface and so at same distance {continuity constraint}.

Focusing on near objects causes ciliary muscles to tighten to increase lens curvature, and kinesthesia sends this feedback to vision system. More tightening and stretching means nearer. Objects farther than two meters cause no muscle tightening or stretching, so accommodation information is useful only for distances less than two meters.

Focusing on near objects causes extraocular muscles to turn eyeballs toward each other, and kinesthesia sends this feedback to vision system. More tightening and stretching means nearer. Objects farther than ten meters cause no muscle tightening or stretching, so convergence information is useful only for distances less than ten meters.

By linear perspective, parallel lines converge, so, for same object, smaller size means farther distance.

Animals continually track distances and directions to distinctive landmarks.

Depth-calculation accuracy and precision are low.

2.9.4. Depth Cues

Various features {depth cue} {cue} signal distance. Depth cues are accommodation, colors, color saturation, contrast, fuzziness, gradients, haziness, distance below horizon, linear perspective, movement directions, occlusions, retinal disparities, shadows, size familiarity, and surface textures.

Non-metrical depth cues can show relative depth, such as object blocking other-object view. Metrical depth cues can show quantitative information about depth. Absolute metrical depth cues can show absolute distance by comparison, such as comparing to nose size. Relative metrical depth cues can show relative distance by comparison, such as twice as far away.

One eye can perceive depth {monocular depth cue}. Monocular depth cues are accommodation, aerial perspective, color, color saturation, edge, monocular movement parallax, occlusion, overlap, shadows, and surface texture.

Adjacent points not at edges are at same distance from eye {continuity constraint}. Scene features land on one retinal location {uniqueness constraint}.

Features farther away are smaller than when closer, so surfaces have larger texture nearby and smaller texture farther away {texture gradient}. Senses can detect gradients by difference ratios. Less fuzzy and larger surface-texture sizes and shapes are nearer, and more fuzzy and smaller are farther.

Vision has less resolution at far distances. Air has haze, smoke, and dust, which absorb redder light, so farther objects are bluer, have less light intensity, and have blurrier edges {aerial perspective} than if air were transparent. (Air scatters blue more than red, but this effect is small except for kilometer distances.)

Higher scene contrast means nearer, and lower contrast means farther. Bluer means farther, and redder means nearer. Edge contrast, edge sharpness, overlap, and transparency depend on contrast.

More blur means farther, and less blur means nearer.

Bluer and hazier surface texture is farther, and redder and less hazy surface texture is closer.

Objects closer to horizon are farther, and objects farther from horizon are nearer. If object is below horizon, higher objects are farther, and lower objects are nearer. If object is above horizon, lower objects are farther, and higher objects are nearer.

Objects that overlap other objects {interposition} are nearer, and objects behind other objects are farther {pictorial depth cue}. Objects with occluding contours are farther. Closer object can hide farther object {occlusion}. Perception knows many rules about occlusion.

At the visual periphery, parallel lines curve, like the effect of a fish eye lens, framing the visual field.

Brain perceives depth using scene points that stimulate right and left eyes differently {binocular depth cue} {binocular depth perception}. Eye convergences, retinal disparities, and surface-area sizes have differences. Brain can judge distance by overlap, total scene area, and area-change rate.

Objects becoming larger are moving closer, and objects becoming smaller are moving away {kinetic depth perception}. Kinetic depth perception is the basis for judging time to collision.

While looking at an object, if observer moves, other objects moving backwards are nearer than object, and other objects moving forwards are farther than object. For farther objects, objects moving faster are nearer, and objects moving slower are farther. For nearer objects, objects moving faster are nearer, and objects moving slower are farther. While observer moves while looking straight ahead, objects moving backwards faster are closer, and objects moving backwards slower are farther.

If objects physically move at same speed, objects moving slower are farther, and objects moving faster are nearer, to a stationary observer.

Fixed object appears to revolve around eye if observer moves.

Some birds use head bobbing to induce motion parallax. Squirrels move orthogonally to objects.

2.10. Eye Movements

Posterior parietal and pre-motor cortex plan and command voluntary eye movements [Bridgeman et al., 1979] [Bridgeman et al., 1981] [Goodale et al., 1986].

Stimulating superior-colliculus neurons can cause angle-specific eye rotation. Stimulating frontal-eye-field or other superior-colliculus neurons makes eyes move to specific locations, no matter from where eye started.

Eyes scan scenes {scanning} in regular patterns along outlines or contours, looking for angles and sharp curves, which give the most shape information.

High-contrast feature or object movements cause eye to turn toward object direction {orientation response}.

During fixations, eye is not still but has tremor {eye tremor} {tremor} over one or two fovea cones, as it also drifts.

Eye muscles exert constant tension against movement, so effort required to move eyes or hold them in position is directly proportional to eye position. Eyes converge toward each other as object gets nearer than 10 meters. In zero-gravity environment, eye resting position shifts upward, but people are not aware of shift.

Visual-cortex neurons {comparator neuron} can receive same output that eye-muscle motor neurons send to eye muscles, so perception can account for eye movements that change scenes.

Brain does not maintain scene between separate images. Perceptual cortex changes only if brain detects change. Perceiving changes requires high-level processing.

If eyes are still with no blinking, scene fades {fading} [Coppola and Purves, 1996] [Pritchard et al., 1960] [Tulunay-Keesey, 1982].

Pupil reflex goes from one eye to the other.

2.10.1. Blinking

People lower and raise eyelids {blinking} every few seconds. Blinking rate increases with anxiety, embarrassment, stress, or distraction, and decreases with concentration. Mind inhibits blinking just before anticipated events.

Eyelids close and open to lubricate eye [Gawne and Martin, 2000] [Skoyles, 1997] [Volkmann et al., 1980].

Blinking can be a reflex to protect eye.

Automatic blinks do not noticeably change scene [Akins, 1996] [Blackmore et al., 1995] [Dmytryk, 1984] [Grimes, 1996] [O'Regan et al., 1999] [Rensink et al., 1997] [Simons and Chabris, 1999] [Simons and Levin, 1997] [Simons and Levin, 1998] [Wilken, 2001].

2.10.2. Saccade

After fixations lasting 120 ms to 130 ms, eye moves {saccade}, in 100 ms, to a new fixation position.

Superior colliculus controls involuntary saccades using fixed vectors in retinotopic coordinates and using endpoint trajectories in head or body coordinates [Bridgeman et al., 1979] [Bridgeman et al., 1981] [Goodale et al., 1986].

People do not have saccades while following moving objects or turning head while fixating objects.

When eye moves from one fixation to another, brain translates whole image up to 100 degrees of arc. World appears to stand still while eyes move, probably because motor signals to move eyes cancel perceptual retinal movement signals.

Automatic saccades do not noticeably change scene [Akins, 1996] [Blackmore et al., 1995] [Dmytryk, 1984] [Grimes, 1996] [O'Regan et al., 1999] [Rensink et al., 1997] [Simons and Chabris, 1999] [Simons and Levin, 1997] [Simons and Levin, 1998] [Wilken, 2001].

Brain does not block input from eye to brain during saccades, but cortex suppresses vision during saccades {saccadic suppression}, so image blurs less. For example, people cannot see their eye movements in mirrors.

2.11. Fixation

To fixate moving visual target, or stationary target when head is moving {fixation}, vertebrates combine vestibular system, vision system, neck somatosensory, and extraocular proprioceptor movement-sensor inputs.

Eyes jump from fixation to fixation, as body, head, and/or eyes move. At each eye fixation, body parts have distances and angles to objects (landmarks). Fixations last long enough to gather new information with satisfactory marginal returns. Fixations eventually gather new information too slowly, so eyes jump again.

During fixations, eye is not still but drifts irregularly {drift} {eye drift} through several minutes of arc, over several fovea cones.

During fixations, eye is not still but moves in straight lines {microsaccade} over 10 to 100 fovea cones.

For fixation, both eyes turn toward each other {convergence} {eye convergence} when objects are nearer than 10 meters. If convergence is successful, there is no retinal disparity. Greater eye convergence means object is closer, and lesser eye convergence means object is farther.

2.12. Focusing

In land-vertebrate eyes, flexible lens focuses {accommodation} image by changing surface curvature using eye ciliary muscles. In fish, an inflexible lens moves backwards and forwards, as in cameras.

Vision focuses image on fovea by making thinnest contour line and highest image-edge gradient [Macphail, 1999].

To accommodate, lens muscles start relaxed, with no accommodation. Brain tightens lens muscles and stops at highest spatial-frequency response.

Lens shape accommodates when objects are less than four feet away. Lens maximum magnification is 15. Far objects require no eye focusing.

Cornea provides two-thirds of light refraction. Non-spherical-cornea astigmatism distorts vision.

Pinhole camera can focus scene, but eye is not pinhole camera.

Good vision means that people can see at 20 feet what perfect-vision people can detect at 20 feet {twenty-twenty}. In contrast, 20-40 means that people can see at 20 feet what perfect-vision people can detect at 40 feet.

If accommodation is for point beyond object, magnification is too low, edges are blurry, and spatial-frequency response is lower, because scene-point light rays land on different retina locations, before they meet at focal point. Focal point is past retina.

If accommodation is for point nearer than object, magnification is too high, edges are blurry, and spatial-frequency response is lower, because scene-point light rays meet at focal point and then land on different retina locations. Focal point is in eye middle.

2.13. Viewpoint

Retina reference frame and object reference frame must match {viewpoint consistency constraint}.

Visual features can stay the same when observation point changes {viewpoint-invariance}. Brain stores such features for visual recognition.

People have a reference point {visual egocenter} {egocenter} on line passing through nosebridge and head center, for specifying locations and directions.

2.14. Visual search

Observers can look {visual search} for objects, features, locations, or times {target} in scenes or lists. Other objects {distractor} are not targets. Search time is directly proportional to number of targets and distractors {set size}.

A parallel process {preattentive stage} suggests serial-search candidates {attentive stage} {guided search theory}.

Searches {feature search} can be for color, size, orientation, shadow, or motion. Feature searches are fastest, because mind searches objects in parallel.

Searches {conjunction search} can be for feature conjunctions, such as both color and orientation. Conjunction searches {serial self-terminating search} can look at items in sequence until finding target. Speed decreases with number of targets and distractors.

Searches {spatial search} can be for feature conjunctions that have shapes or patterns, such as two features that cross. Mind performs spatial searches in parallel but can only search feature subsets {limited capacity parallel process}.

2.15. Location perception

Vision can detect location along radial lines. Vision detects only one source from one location. Vision receives from many locations simultaneously. Eyes have one million radial lines.

Vision detects smallest visual angle {visual acuity} {acuity}.

Scene features have diameter, whose ends define rays that go to eye-lens center to form angle {visual angle}.

Visual angles land on retinal areas, which send to larger visual-cortex surface areas {cortical magnification}.

Vision accurately knows surface tilt and slant, directly, by tilt angle itself, not by angle function [Bhalla and Proffitt, 1999] [Proffitt et al., 1995].

2.16. Size perception

Observers do not know actual object sizes but only judge relative sizes.

If they look at too few lines {undersampling}, people estimate grating size incorrectly {aliasing}.

2.17. Texture Perception

Visual perceptual processes can detect local surface properties {surface texture} {texture perception} [Rogers and Collett, 1989] [Yin et al., 1997].

Surface textures are point and line patterns, with densities, locations, orientations, and gradients. Surface textures have point and line spatial frequencies [Bergen and Adelson, 1988] [Bülthoff et al., 2002] [Julesz, 1981] [Julesz, 1987] [Julesz and Schumer, 1981] [Lederman et al., 1986] [Malik and Perona, 1990].

Similar surface textures have similar point and line spatial frequencies and first-order and second-order statistics [Julesz and Miller, 1962].

Texture gradients are proportional to surface slant, surface tilt, object size, object motion, shape constancy, surface smoothness, and reflectance.

Surface-texture detection can use point and line features, such as corner detection, scale-invariant features (SIFT), and speeded-up robust features (SURF) [Wolfe and Bennett, 1997]. For example, in computer vision, the Gradient Location-Orientation Histogram (GLOH) SIFT descriptor uses radial grid locations and gradient angles, then finds principal components, to distinguish surface textures [Mikolajczyk and Schmid, 2005].

Surfaces have small regular repeating units {texel}.

Texture perception uses three local-feature types {texton}: elongated blobs {line segment}, blob ends {end-point}, and blob crossings {texture}. Visual-cortex simple and complex cells detect elongated blobs, terminators, and crossings. Texture perception searches in parallel for texton type and density changes. Texture discrimination precedes attention. For texton changes, brain calls attention processes. If elongated blobs are same, because blob terminators total same number, texture is same. Brain uses first-order texton statistics, such as texton type changes and density gradients, in texture perception.

Occipital-lobe complex and hypercomplex cells detect points, lines, surfaces, line orientations, densities, and gradients and send to neuron assemblies that detect point and line spatial frequencies [DeValois and DeValois, 1988] [Hubel and Wiesel, 1959] [Hubel and Wiesel, 1962] [Hubel, 1988] [Livingstone, 1998] [Spillman and Werner, 1990] [Wandell, 1995] [Wilson et al., 1990].

Constant texture gradient indicates one object. Similar texture patterns indicate same surface region. Brain can use texture differences to separate surface regions.

Brain detects many targets rapidly and simultaneously to select and warn about approaching objects. Brain can detect textural changes in less than 150 milliseconds, before attention begins.

2.18. Pattern Recognition

Vision processes can recognize patterns {pattern recognition} {shape perception}. Patterns have objects, features, and spatial relations. Patterns can have points, lines, angles, waves, histograms, grids, and geometric figures. Patterns, pattern surroundings, and/ background have brightness, hue, saturation, shape, size, position, and motion.

The first and main pattern-recognition mechanism is association (associative learning). Complex recognition uses multiple associations.

For feature detection, brain can use classifying context or constrain classification {relational matching}.

Pattern-precognition processing has three levels. Processing depends on effective inputs and useful outputs {computational level}. Processing uses functions to go from input to output {algorithmic level}. Processing machinery performs algorithms {physical level} [Marr, 1982].

Pattern recognition can use conscious memory {explicit recognition} [McDougall, 1911] [McDougall, 1923]. Pattern recognition can be automatic {implicit recognition}, like reflexes.

To recognize structure, brain can use information about that structure {instructionism} or compare to multiple variations and select best match {selectionism}, just as cells try many antibodies to bind antigen.

Pattern recognition depends on alertness and attention.

Recall easiness varies with attention amount, emotion amount, cue availability, and/or previous-occurrence frequency.

Mind recognizes music by rhythm or by intonation differences around main note. People can recognize rhythms and rhythmic groups. People can recognize melodies transformed from another melody. People most easily recognize same melody in another key. People easily recognize melodies that exchange high notes for low. People can recognize melodies in reverse. People sometimes recognize melodies with both reverse and exchange.

Bees can recognize colors, except reds, and do circling and wagging dances, which show food-source angle, direction, distance, and amount. Frogs can recognize prey and enemy categories [Lettvin et al., 1959]. Apes recognize objects using fast multisensory processes and slow single-sense processes, but do not transfer learning from one sense to another.

2.18.1. Neurons

Some brain neurons {grandmother cell} {grandmother neuron} {Gnostic neuron} {place cell} can recognize a perception or store a concept [Barlow, 1972] [Barlow, 1995] [Gross, 1998] [Gross, 2002] [Gross et al., 1969] [Gross et al., 1972] [Konorski, 1967]. Place cells recognize textures, objects, and contexts.

Some cortical cells {face cell} respond only to frontal faces, profile faces, familiar faces, facial expressions, face's gaze direction, hairbrush, or hand. Face cells are in inferior-temporal cortex, amygdala, and other cortex. Face-cell visual field is whole fovea. Color, contrast, and size do not affect face cells [Perrett et al., 1992].

Secondary visual cortex neurons can detect line orientation, have large receptive fields, and have variable topographic mapping.

Cerebral cortex can separate feature from feature mixture.

Brain-register network can store pattern information, and brain-register network series can store processes and pattern changes.

Neuron dendrite and cell-body synapses contribute different potentials to axon initial region. Input distributions represent patterns, such as geometric figures. Different input-potential combinations can trigger neuron impulses. As in statistical mechanics, because synapse number is high, one input-potential distribution has highest probability. Neurons detect that distribution and no other. Learning and memory can change cell and affect distribution detected.

2.18.2. Number perception

Brain can count {number perception}. Number perception can relate to time-interval measurement, because both measure number of units [Dehaene, 1997].

Number perception can add energy units to make sum {accumulator model} [Dehaene, 1997].

Number perception can associate objects with ordered-symbol list {numeron list model} [Dehaene, 1997].

Number perception can use mental images in arrays, so objects are separate {object file model} [Dehaene, 1997].

2.18.3. Shape perception

Vision can recognize geometric features {shape} {pattern}.

Shapes have lines, line orientations, and edges. Contour outlines indicate objects and enhance brightness and contrast. Irregular contours and hatching indicate movement. Contrast enhances contours, for example with Mach bands. Contrast differences divide large surfaces into parts.

Shapes have natural position axes, such as vertical and horizontal, and natural shape axes, such as long axis and short axis. Vision uses horizontal, vertical, and radial axes for structure and composition.

Objects are wholes and have parts. Wholes are part integrations or configurations and are about gist. Parts are standard features and are about details.

Shape has surfaces, with surface curvatures, orientations, and vertices. Visual system can label lines and surfaces as convex, concave, or overlapping [Grunewald et al., 2002]. Shapes have shape-density functions, with projections onto axes or chords [Grunewald et al., 2002]. Shapes have distances and natural metrics, such as lines between points.

Shapes have illuminance and reflectance.

Shapes have axis and chord ratios {area eccentricity} [Grunewald et al., 2002].

Shapes have perimeter squared divided by area {compactness} [Grunewald et al., 2002].

Shapes have minimum chain-code sequences that make shape classes {concavity tree}, which have maximum and minimum concavity-shape numbers [Grunewald et al., 2002].

Shapes have connectedness {Euler number} [Grunewald et al., 2002].

For recognition, spatial organization and overall pattern are more important than parts. Frequency is more important than recency. Parts are more important for nearby objects. Recognition processing ignores siz and left-right orientation.

Vision uses contrast for boundary making.

Vision can connect pieces in sequence and fill gaps.

Sharp brightness or hue difference indicates edge or line {edge detection}. Point clustering indicates edges. Vision uses edge information to make object boundaries and adds information about boundary positions, shapes, directions, and noise. Neuron assemblies have different spatial scales to detect different-size edges and lines. Tracking and linking connect detected edges.

Vision separates scene features into belonging to object and not belonging {segmentation problem}. Large-scale analysis is first and then local constraints. Context hierarchically divides image into non-interacting parts.

If brain knows reflectance and illumination, shading {shading} can reveal shape. Line and edge detectors can find shape from shading.

Vision generalizes patterns by eliminating one dimension, using one subpattern, or including outer domains.

Vision can label vertices as three-intersecting-line combinations {vertex perception}. Intersections can be convex or concave, to right or to left.

Pattern recognition uses shortest line, extends line, or links lines.

Object or event classification involves high-level feature recognition, not direct object or event identification. Brain extracts features and feeds forward to make hypotheses and classifications. For example, people can recognize meaningful facial expressions and other complex perceptions in simple drawings that have key features [Carr and England, 1995].

Templates have non-accidental and signal properties that define object classes. Categories have rules or criteria. Vision uses structural descriptions to recognize patterns. Brains compare input patterns to template using constraint satisfaction on rules/criteria and then selecting best-fitting match, by score. If input activates one representation strongly and inhibits others, representation sends feedback to visual buffer, which then augments input image and modifies or completes input image by altering size, location, or orientation. If representation and image then match even better, mind recognizes object. If not, mind inhibits that representation and activates next representation.

Vision can reconstruct how object appears from any viewpoint using a minimum of two, and a maximum of six, different-viewpoint images. Vision calculates object positions and motions from three views of four non-coplanar points. To recognize objects, vision interpolates between stored representations. Mind recognizes symmetric objects better than asymmetric objects from new viewpoints. Recognition fails for unusual viewpoints.

Vision finds, separates, and labels visual areas by enlarging spatial features or partitioning scenes {region analysis}. Progressive entrainment of larger and larger cell populations builds regions using synchronized firing. Regions form by clustering features, smoothing differences, relaxing/optimizing, and extending lines using edge information. Regions can form by splitting spatial features or scenes. Parallel circuits break large domains into similar-texture subdomains for texture analysis. Parallel circuits find edge ends by edge interruptions.

To recognize letters, on all four sides, check for point, line, corner, convex curve, W or M shape, or S or squiggle shape. 6^4 = 1296 combinations are available. Letters, numbers, and symbols add to less than 130, so symbol recognition is robust [Pao and Ernst, 1982].

Will a blind person that knows shapes by touch recognize the shapes if able to see {Molyneux problem}? Testing cataract patients after surgery has not yet resolved this question.

Pattern recognition uses gray-level changes, not colors. Motion detection uses gray-level and pattern changes.

Mind recognizes objects with translation-invariant features more easily if they are moving. People can recognize objects that they see moving behind a pinhole.

Machines can find, count, and measure picture object areas; classify object shapes; detect colors and textures; and analyze one image, two stereo images, or image sequences. Recognition algorithms have scale invariance.

2.18.4. Scenes

The feeling of seeing whole scene {scene} results from maintaining general scene sense in semantic memory, attending repeatedly to scene objects, and forming object patterns. Vision experiences whole scene (perceptual field), not just isolated points, features, surfaces, or objects. Perceptual field provides background and context, which can identify objects and events.

Scenes have different spatial frequencies in different directions and distances. Scenes can have low spatial frequency and seem open. Low-spatial-frequency scenes have more depth, less expansiveness, and less roughness, and are more natural. Scenes can have high spatial frequency and seem closed. High-spatial-frequency scenes have less depth, more expansiveness, and more roughness, and are more about towns.

Scenes have numbers of objects {set size}.

Scenes have patterns or structures of object and object-property placeholders {spatial layout}, such as smooth texture, rough texture, enclosed space, and open space. In spatial layouts, object and property meanings do not matter, only placeholder pattern. Objects and properties can fill object and object property placeholders to supply meaning. Objects have spatial positions, and relations to other objects, that depend on spacing and order. Spatial relations include object and part separations, feature and part conjunctions, movement and orientation directions, and object resolution.

Scenes have homogeneous color and texture regions {visual unit}.

2.18.5. Mathematical methods

Patterns can have algorithm-generated unique, unambiguous, and meaningful index numbers. Running reverse algorithm generates pattern from index number. Similar patterns have similar index numbers. Patterns differing by subpattern have index numbers that differ only by ratio or difference. Index numbers have information about shape, parts, and relations, not about size, distance, orientation, incident brightness, incident light color, and viewing angle. Index numbers can be power series. Term coefficients are weights. Term sums are typically unique numbers. For patterns with many points, index number is large, because information is high.

Patterns have a unique point, like gravity center. Pattern points have unique distances from unique point. Power-series terms are for pattern points. Term sums are typically unique numbers that depend only on coordinates internal to pattern. Patterns differing by subpattern differ by ratio or difference.

Features can remain invariant as images deform or move. Holding all variables, except one, constant can find the derivative with respect to the non-constant variable, and so calculate partial differentials to measure changes/differences and find invariants.

Differentiation subtracts second derivative from intensity and emphasizes high frequencies.

Brain uses statistics to assign probability to patterns recognized. Vision can use dynamic programming to optimize parameters.

Matching can use heuristic search to find feature or path. Low-resolution search over whole image looks for matches to feature templates.

HBF or RBF basis functions can separate scene into multiple dimensions. Vision can separate scene into additive parts, by boundaries, rather than using basis functions.

Averaging removes noise by emphasizing low frequencies and minimizing high frequencies.

Pattern recognition can place classes or subsets in clusters in abstract space.

Motion change and retinal disparity are equivalent perceptual problems, so finding distance from retinal disparity and finding shape from motion {shape from motion} changes use equivalent techniques.

2.18.6. Algorithms

To identify objects, algorithms can test patterns against feature sets. If patterns have features, algorithms add distinctiveness weight to object distinctiveness-weight sum. If object has sum greater than threshold {detection threshold} {threshold of detection}, algorithm identifies pattern as object. Context sets detection threshold.

In recognition algorithms, object features can have weights {distinctiveness weight}, based on how well feature distinguishes object from other objects. Algorithm designers use feature-vs.-weight tables or automatically build tables using experiences.

Algorithms {Gabor transform} {Gabor filter} can make series, whose terms are for independent visual features, have constant amplitude, and have functions. Term sums are series [Palmer et al., 1991]. Visual-cortex complex cells act like Gabor filters with power series. Terms have variables raised to powers. Complex-cell types are for specific surface orientation and object size. Gabor-filter complex cells typically make errors for edge gaps, small textures, blurs, and shadows.

Non-parametric algorithms {histogram density estimate} can calculate density. Algorithm tests various cell sizes by nearest-neighbor method or kernel method. Density is average volume per point.

Using Bayesian theory, algorithms {image segmentation} can extend edges to segment image and surround scene regions.

Algorithms {kernel method} can test various cell sizes, to see how small volume must be to have only one point.

Algorithms {linear discriminant function} (Fischer) can find abstract-space hypersurface boundary between space regions (classes), using region averages and covariances.

Algorithms {memory-based models} (MBM) can match input-pattern components to template-pattern components, using weighted sums, to find highest scoring template. Scores are proportional to similarity. Memory-based models uniquely label component differences. Memory-based recognition, sparse-population coding, generalized radial-basis-function (RBF) networks, and hyper-basis-function (HBF) networks are similar algorithms.

Algorithms {nearest neighbor method} can test various cell sizes to see how many points (nearest neighbor) are in cells.

Algorithms {pattern matching} can try to match two network representations by two parallel searches, starting from each representation. Searches look for similar features, components, or relations. When both searches meet, they excite the intermediate point (not necessarily simultaneously), whose signals indicate matching.

Algorithms {pattern theory} can use feedforward and feedback processes and relaxation methods to move from input pattern toward memory pattern. Algorithm uses probabilities, fuzzy sets, and population coding, not formal logic.

For algorithms or observers, graphs {receiver operating characteristics} (ROC) can show true identification-hit rate versus false-hit rate. If correlation line is 45-degree-angle straight line, observer has as many false hits as true hits. If correlation line has steep slope, observer has mostly true hits and few false hits. If correlation line has maximum slope, observer has zero false hits and all true hits.

Algorithms {response bias} can use recognition criteria iteratively set by receiver operability curve.

Algorithms {signal detection theory} can find patterns in noisy backgrounds. Patterns have stronger signal strength than noise. Detectors have sensitivity and response criteria.

Algorithms {generalized cone} can describe three-dimensional objects as conical shapes, with axis length/orientation and circle radius/orientation. Main and subsidiary cones can be solid, hollow, inverted, asymmetric, or symmetric. Cone surfaces have patterns and textures [Marr, 1982]. Cone descriptions can use three-dimensional Fourier spherical harmonics, which have volumes, centroids, inertia moments, and inertia products.

Algorithms {generalized cylinder} can describe three-dimensional objects as cylindrical shapes, with axis length/orientation and circle radius/orientation. Main and subsidiary cylinders can be solid, hollow, inverted, asymmetric, or symmetric. Cylindrical surfaces have patterns and textures. Cylinder descriptions can use three-dimensional Fourier spherical harmonics, which have volumes, centroids, inertia moments, and inertia products.

2.18.7. Production systems

Classification algorithms {production system} can use IF/THEN rules on input to conditionally branch to one feature or object. Production systems have three parts: fact database, production rule, and rule-choosing control algorithm. Fact-database entries code for one state {local representation}, allowing memory. Production rules have form "IF State A, THEN Process N". Rules with same IF clause have one precedence order. Controller checks all rules, performing steps in sequence {serial processing}. For example, if system is in State A and rule starts "IF State A", then controller performs Process N, which uses fact-database data. Discrete systems have state spaces whose axes represent parameters, with possible values. System starts with initial-state parameter settings and moves from state to state, along a trajectory, as controller applies rules.

Production systems have rules {production rule} for moving from one state to the next. Production rules have form "IF State A, THEN Process N". Rules with same IF clause have one precedence order.

Parallel pattern-recognition mechanisms can fire whenever they detect patterns {ACT production system}. Firing puts new data elements in working memory.

Same production can match same data only once {Data Refractoriness production system}.

Production with best-matched IF-clause can have priority {Degree of Match production system}.

Goals are productions put into working memory. Only one goal can be active at a time {Goal Dominance}, so productions whose output matches active goal have priority.

Recently successful productions can have higher strength {Production Strength production system}.

Parallel pattern-recognition mechanisms can fire whenever they detect particular patterns {Soar production system}. Firing puts new data elements in working memory.

If two productions match same data, production with more-specific IF-clause wins {Specificity production system}.

2.18.8. Representations

Neuron assemblies can hold essential knowledge about patterns {explicit representation}, using information not in implicit representation. Mind calculates explicit representation from implicit representation, using feature extraction or neural networks [Kobatake et al., 1998] [Logothetis and Pauls, 1995] [Logothetis et al., 1994] [Sheinberg and Logothetis, 2001].

Neuron or pixel sets can hold object image {implicit representation}, with no higher-level knowledge. Implicit representation samples intensities at positions at times, like bitmaps [Kobatake et al., 1998] [Logothetis and Pauls, 1995] [Logothetis et al., 1994] [Sheinberg and Logothetis, 2001].

Representations can describe object parts and spatial relations {structural description}. Structure units can be three-dimensional generalized cylinders (Marr), three-dimensional geons (Biederman), or three-dimensional curved solids {superquadratics} (Pentland). Structural descriptions are only good for simple recognition {entry level recognition}, not for superstructures or substructures. Vision uses viewpoint-dependent recognition, not structural descriptions.

Shape representations {template} can hold information for mechanisms to use to replicate or recognize {template theory} {naive template theory}. Template is like memory, and mechanism is like recall. Template can be coded units, shape, image, model, prototype, or pattern. Artificial templates include clay or wax molds. Natural templates are DNA/RNA. Templates can be abstract-space vectors. Using templates requires templates for all viewpoints, and so many templates.

Representations {vector coding} can be sense-receptor intensity patterns and/or brain-structure neuron outputs, which make feature vectors. Vector coding can identify rigid objects in Euclidean space. Vision uses non-metric projective geometry to find invariances by vector analysis [Staudt, 1847] [Veblen and Young, 1918]. Motor-representation middle and lower levels use code that indicates direction and amount.

2.18.9. Mental rotation

Vision can manipulate images to see if two shapes correspond. Vision can zoom, rotate, stretch, color, and split images {mental rotation} [Shepard and Metzler, 1971] [Shepard and Cooper, 1982].

Images transform by high-level perceptual and motor processing, not sense-level processing. Image movements follow abstract-space trajectories or proposition sequence.

Motor processes transform visual mental images, because spatial representations are under motor control [Sheikh, 1983].

People require more time to perform mental rotations that are physically awkward. Vision compares aligned images faster than translated, rotated, or inverted images.

2.18.10. Mirror recognition

Animals and human infants recognize that their images in mirrors are species members, but they do not recognize themselves. Perhaps, they have no mirror-reflection concept. Children and adults immediately recognize their images in mirrors {mirror recognition}. Chimpanzees, orangutans, bonobos, and two-year-old humans, but not gorillas, baboons, and monkeys, can recognize themselves in mirrors after using mirrors for a time [Gallup, 1970].

Pigeons, monkeys, and apes can use mirrors to guide movements. Some apes can touch body spots that they see in mirrors. Chimpanzees, orangutans, bonobos, and two-year-old humans, but not gorillas, baboons, and monkeys, can use mirror reflections to perceive body parts and to direct actions [Gallup, 1970].

Autistic children use mirrors normally but appear to have no theory of mind. Animals have no theory of mind.

2.19. Binocular Vision

Vision combines output from both eyes {binocular vision}. Cats, primates, and predatory birds have binocular vision. Binocular vision allows stereoscopic depth perception, increases light reception, and detects differences between camouflage and surface. During cortex-development sensitive period, what people see determines input pathways to binocular cells and orientation cells [Blakemore and Greenfield, 1987] [Cumming and Parker, 1997] [Cumming and Parker, 1999] [Cumming and Parker, 2000].

Scene features have different left-retina and right-retina positions. Retina can use low resolution, with low spatial frequency, to analyze big regions and then use higher and higher resolutions.

One stimulus can affect both eyes, and effects can add {binocular summation}.

Visual-cortex cells {disparity detector} can combine right and left eye outputs to detect relative position disparities. Disparity detectors receive input from same-orientation orientation cells at different retinal locations. Higher binocular-vision cells detect distance directly from relative disparities, without form or shape perception.

People using both eyes do not know which eye {eye-of-origin} saw something [Blake and Cormack, 1979] [Kolb and Braun, 1995] [Ono and Barbieto, 1985] [Pickersgill, 1961] [Porac and Coren, 1986] [Smith, 1945] [Helmholtz, 1856] [Helmholtz, 1860] [Helmholtz, 1866] [Helmholtz, 1962].

Eye focuses at a distance, through which passes a vertical plane {fixation plane} {plane of fixation}, perpendicular to sightline. From that plane's points, eye convergence can make right and left eye images almost correspond, with almost no disparity. From points in a circle {Vieth-Müller circle} in that plane, eye convergence can make right and left eye images have zero disparity.

After eye fixation on scene point and eye convergence, an imaginary sphere {horopter} passes through both eye lenses and fixation point. Points from horopter land on both retinas with same azimuthal and elevation angles and same absolute disparities. These scene points have no relative disparity and so have single vision.

Brain fuses scene features that are inside distance from horopter {Panum's fusion area} {Panum fusion area} {Panum's fusional area}, into one feature. Brain does not fuse scene features outside Panum's fusional area, but features still register in both eyes, so feature appears double.

Brain stimuli {cyclopean stimulus} can result only from binocular disparity.

Adaptation can transfer from one eye to the other {interocular transfer}.

2.19.1. Binocular disparity

Right and left retinas see different images {retinal disparity} {binocular disparity} [Dacey et al., 2003] [DeVries and Baylor, 1997] [Kaplan, 1991] [Leventhal, 1991] [MacNeil and Masland, 1998] [Masland, 2001] [Polyak, 1941] [Ramòn y Cajal, 1991] [Rodieck et al., 1985] [Rodieck, 1998] [Zrenner, 1983].

Vision has disparity detectors [Blakemore and Greenfield, 1987].

Brain can correlate retinal images to pair scene retinal points and then find distances and angles.

Assume eye fixates on a point straight-ahead. Light ray from scene point forms horizontal azimuthal angle and vertical elevation angle with straight-ahead direction. With no eye convergence, eye azimuthal and elevation angles from scene point differ {absolute disparity}. Different scene points have different absolute disparities {relative disparity}.

When both eyes fixate on same scene point, eye convergence places scene point on both eye foveas at corresponding retinal points, azimuthal and elevation angles are the same, and absolute disparity is zero. After scene-point fixation, azimuth and elevation angles differ for all other scene points. Brain uses scene-point absolute-disparity differences to find relative disparities to estimate relative depth.

Points from horopter land on both retinas with same azimuthal and elevation angles and same absolute disparities. These scene points have no relative disparity and so have single vision. Points not close to horopter have different absolute disparities, have relative disparity, and so have double vision.

With eye fixation on far point between eyes and with eye convergence, if scene point is straight-ahead, between eyes, and nearer than fixation distance, point lands outside fovea, for both eyes. For object closer than fixation plane, focal point is after retina {crossed disparity}.

With eye fixation on close point between eyes and eye convergence, if scene point is straight-ahead, between eyes, and farther than fixation distance, point lands inside fovea, for both eyes. For object farther than fixation plane, focal point is before retina {uncrossed disparity}.

Two eyes can measure relative distance to point by retinal disparity.

Retinal disparity and motion change are equivalent perceptual problems, so finding distance from retinal disparity and finding lengths and shape from motion changes use similar techniques.

2.20. Time

Vision is in real time, with a half-second delay.

Reaction to visual perception takes 450 milliseconds [Bachmann, 2000] [Broca and Sulzer, 1902] [Efron, 1967] [Efron, 1970] [Efron, 1973] [Taylor and McCloskey, 1990] [Thorpe et al., 1996] [VanRullen and Thorpe, 2001].

Visual features can blend {feature inheritance} [Herzog and Koch, 2001]. Stimuli blend if less than 200 milliseconds apart {flicker fusion frequency} [Efron, 1973] [Fahle, 1993] [Gowdy et al., 1999] [Gur and Snodderly, 1997] [Herzog et al., 2003] [Nagarajan et al., 1999] [Tallal et al., 1998] [Yund et al., 1983] [Westheimer and McKee, 1977].

Vision habituates slowly.

2.21. Motion perception

Brain can perceive motion {motion perception} {motion detector}. Motion analysis is independent of other visual analyses.

For moving objects, eyes keep object on fovea, then fall behind, then jump to put object back on fovea {smooth pursuit}. Smooth pursuit is automatic. People cannot voluntarily use smooth pursuit. Smooth pursuit happens even if people have no sensations of moving objects [Thiele et al., 2002].

Retinal radial-image speed relates to object distance. Vision can detect that surface is approaching eye {looming response}. Looming response helps control flying and mating.

Three-month-old infants understand {Theory of Body} that when moving objects hit other objects, other objects move. Later, infants understand {Theory of Mind Mechanism} self-propelled motion and goals. Later, infants understand {Theory of Mind Mechanism-2} how mental states relate to behaviors. Primates can understand that acting on objects moves contacted objects.

While observer is moving, nearer objects seem to move backwards while farther ones move in same direction as observer {monocular movement parallax}.

Luminance changes indicate motion {first-order motion}. Contrast and texture changes indicate motion {second-order motion}.

Objects {luminance-defined object}, for example bright spots, can contrast in brightness with background. People see luminance-defined objects move by mechanism that differs from texture-defined object-movement mechanism. Luminance-defined objects have defined edges. Objects {texture-defined object} {contrast-defined object} can contrast in texture with background. People see luminance-defined objects move by mechanism that differs from texture-defined object-movement mechanism. Contrast changes in patterned ways, with no defined edges.

To have right and left requires asymmetry, such as dot or shape. In rotation, one side appears to go backward while the other goes forward, which makes whole thing stand still.

Brain action pathway is faster than object-recognition pathway. Brain calculates eye movements faster than voluntary movements.

Animal species have movement patterns {biological motion}. Distinctive motion patterns, such as falling leaf, pouncing cat, and swooping bat, allow object recognition and future position prediction.

Vision improves motor control by locating and recognizing objects.

2.21.1. Neurons

Most cortical motion-detector neurons detect motion direction, are for specific distance, are for specific space direction, are for specific object spot or line size, and detect motion speed. Area-V5 neurons detect different speed motions in different directions at different distances and locations for different object spot or line sizes. Motion detectors are for one direction, object size, distance, and speed relative to background. Other neurons detect expansion, contraction, and right or left rotation [Thier et al., 1999]. Motion-detector array represents three-dimensional space.

Motion-detector neurons can fatigue. Motion detector neurons adapt quickly.

To detect larger or smaller objects, motion-detector neurons have larger or smaller receptive fields.

Spot motion from one place to another is like appearance at location and then appearance at another location. Spot must excite motion-detector neuron for that direction and distance.

Motion detectors interact, so motion inhibits opposed motion, making motion contrasts. For example, motion in one direction excites motion detectors for that direction and inhibits motion detectors for opposite direction.

Motion-detector-neuron comparison is not simultaneous addition but has delay or hold from first neuron to wait for second excitation. Delay can be long, with many intermediate neurons, far-apart neurons, or slow motion, or short, with one intermediate neuron, close neurons, or fast motion.

Motion detectors work together to detect trajectory or measure distances, velocities, and accelerations. Higher-level neurons connect motion detection units to detect straight and curved motions (Werner Reichardt). As motion follows trajectory, memory shifts to predict future motions.

Regions {horizontal gaze center}, near pons abducens nucleus, can detect right-to-left and left-to-right motions.

Regions {vertical gaze center}, near midbrain oculomotor nucleus, can detect up and down motions.

2.21.2. Motion parallax

Head or body movement causes scene retinal displacement. Nearer objects displace more, and farther objects displace less {motion parallax} {movement parallax}. If eye moves to right while looking straight-ahead, objects appear to move to left.

Nearer objects move greater visual angle. Farther objects move smaller visual angle and appear almost stationary.

Object sequence can change with movement.

Brain can use geometric information about two different positions at different times to calculate relative object depth. Brain can also use geometric information about two different positions at same time, using both eyes.

2.21.3. Moving spots

When viewing moving object through small opening, motion direction can be ambiguous {aperture problem}, because moving spot or two on-off spots can trigger motion detectors. Are both spots in window aperture same object? Motion detectors solve the problem by finding shortest-distance motion.

When people see objects, first at one location, then very short time later at another location, and do not see object anywhere between locations, first object seems to move smoothly to where second object appears {apparent motion}.

Moving spot triggers motion detectors for two locations.

How does brain associate two locations with one spot {correspondence problem}? Brain follows spot from one location to next unambiguously. Tracking moving objects requires remembering earlier features and matching with current features. Vision can try all possible matches and, through successive iterations, find matches that yield minimum total distance between presentations.

Turning one spot on and off can trigger same motion detector. How does brain associate detector activation at different times with one spot? Brain assumes same location is same object.

If an image or light spot appears on a screen and then a second image appears 0.06 seconds later at a randomly different location, people perceive motion from first location to second location {phi phenomenon}. If an image or light spot blinks on and off slowly and then a second image appears at a different location, people see motion. If a green spot blinks on and off slowly and then a red spot appears at a different location, people see motion, and dot appears to change color halfway between locations.

2.21.4. Optic Flow

Light rays reflect from visual-field objects, forming a two-dimensional array {optic array} [Gibson, 1966] [Gibson, 1979].

Incoming visual information is continuous flow {visual flow} {optical flow} {optic flow} that brain can analyze for constancies, gradients, motion, and static properties. As head or body moves, head moves through stationary environment. Optical flow reveals whether one is in motion or not. Optical flow reveals planar surfaces. Optical flow is texture movement across eye as animals move.

Optic flow has a point {focus of expansion} (FOE) {expansion focus} where horizon meets motion-direction line. All visual features seem to come out of this straight-ahead point as observer moves closer, making radial movement pattern {radial expansion} [Gibson, 1966] [Gibson, 1979].

Optic flow has information {tau} that signals how long until something hits people {time to collision} (TTC) {collision time}. Tau is ratio between retinal-image size and retinal-image-size expansion rate. Tau is directly proportional to time to collision.

2.21.5. Throw and catch

Mammals can throw and catch {throwing} {catching}.

Animals can move in direction, change direction, turn around, and wiggle. Animals can move faster or slower. Animals move over horizontal ground, climb up and down, jump up and down, swim, dive, and fly.

Predators typically intercept moving prey, trying to minimize separation. In reptiles, optic tectum controls visual-orientation movements used in prey-catching behaviors. Prey typically runs away from predators, trying to maximize separation. Animals must account for accelerations and decelerations.

Animals must account for gravity as they move and catch. Some hawks free-fall straight down to surprise prey. Seals can catch thrown balls and can throw balls to targets. Dogs can catch thrown balls and floating frisbees. Cats raise themselves on hind legs to trap or bat thrown-or-bouncing balls with front paws.

Reticular formation, hippocampus, and neocortex are only in mammals. Mammal superior colliculus can integrate multisensory information at same spatial location [O'Regan and Noë, 2001]. In mammals, dorsal vision pathway indicates object locations, tracks unconscious motor activity, and guides conscious actions [Bridgeman et al., 1979] [Rossetti and Pisella, 2002] [Ungerleider and Mishkin, 1982] [Yabuta et al., 2001] [Yamagishi et al., 2001].

Mammal dorsal visual system converts spatial properties from retinotopic coordinates to spatiotopic coordinates. Using stationary three-dimensional space as fixed reference frame simplifies trajectories perceptual variables. Most motions are two-dimensional rather than three-dimensional. Fixed reference frame separates gravity effects from internally generated motions. Internally generated motion effects are straight-line motions, rather than curved motions.

Only primates can throw, because they can stand upright and have suitable arms and hands. From 45,000 to 35,000 years ago, Homo sapiens and Neanderthal Middle-Paleolithic hunter-gatherers cut and used wooden spears. From 15,000 years ago, Homo sapiens Upper Paleolithic hunter-gatherers cut and used wooden arrows, bows, and spear-throwers. Human hunter-gatherers threw and shot over long trajectories.

Geometric Invariants: Humans can catch objects traveling over long trajectories. Dogs and humans use invariant geometric properties to intercept moving objects.

Trajectory Prediction: To catch baseballs, eyes follow ball while people move toward position where hand can reach ball. In the trajectory prediction strategy [Saxberg, 1987], fielder perceives ball initial direction, velocity, and perhaps acceleration, then computes trajectory and moves straight to where hand can reach ball.

Acceleration Cancellation: When catching ball coming towards him or her, fielder must run under ball so ball appears to move upward at constant speed. In the optical-acceleration-cancellation hypothesis [Chapman, 1968], fielder motion toward or away from ball cancels ball perceived vertical acceleration, making constant upward speed. If ball appears to vertically accelerate, it lands farther than fielder. If it appears to vertically decelerate, it lands shorter. Ball rises until caught, because baseball is always above horizon, far objects are near horizon, and near objects are high above horizon.

Transverse Motion: Fielder controls transverse motion independently of radial motion. When catching ball toward right or left, fielder moves transversely to ball path, holding ball-direction and fielder-direction angle constant.

Linear Trajectory: In linear optical trajectory [McBeath et al., 1995], when catching ball to left or right, fielder runs in a curve toward ball, so ball rises in optical height, not to right or left. Catchable balls appear to go straight. Short balls appear to curve downward. Long balls appear to curve upward. Ratio between ball elevation and azimuth angles stays constant. Fielder coordinates transverse and radial motions. Linear optical trajectory is similar to simple predator-tracking perceptions. Dogs use the linear optical trajectory method to catch frisbees [Shaffer et al., 2004].

Optical Acceleration: Plotting optical-angle tangent changes over time, fielders appear to use optical-acceleration information to catch balls [McLeod et al., 2001]. However, optical trajectories mix fielder motions and ball motions.

Perceptual Invariants: Optical-trajectory features can be invariant with respect to fielder motions. Fielders catch fly balls by controlling ball-trajectory perceptions, such as lateral displacement, rather than by choosing how to move [Marken, 2005].

2.22. Change blindness

People often do not see scene changes or anomalies {change blindness}, especially if overall meaning does not change.

When scene changes during eye blinks, people do not see differences.

When scene changes during saccades, people do not see differences.

People do not see gradual changes.

People do not see changes when masking hides scene changes.

When a featureless gray picture flashes between views of first scene and slightly-different second scene, people do not see differences.

If attentional load increases, change blindness increases.

Repeated stimuli can lead to not seeing {repetition blindness}, especially if overall meaning does not change [Kanwisher, 1987].

2.23. Mirror reversal

As observer looks in a plane mirror, mirror reflects observer top, bottom, right, and left at observed top, bottom, right, and left. Observer faces in opposite direction from reflection, reflection right arm is observer left arm, and reflection left arm is observer right arm, as if observer went through mirror and turned front side back (inside out) {mirror reversal}.

Reflection through one point causes reflection and rotation (inversion). Inversion makes right become left, left become right, top become bottom, and bottom become top. Plane mirrors do not reflect through one point.

If an object is between observer and mirror, observer sees object front, and mirror reflects object back. Front top is at observer top, front bottom is at observer bottom, front right is at observer left, and front left is at observer right. Back top is at observer top, back bottom is at observer bottom, back right is at observer right, and back left is at observer left. It is like object has rotated horizontally 180 degrees. Mirrors cause rotation {mirror rotation}. 180-degree horizontal rotation around vertical axis exchanges right and left. 180-degree vertical rotation around right-left horizontal axis exchanges top and bottom. 180-degree vertical rotation around front-back horizontal axis exchanges right and left and top and bottom.

If a transparent glass sheet has writing on the back side facing a plane mirror, observers looking at the glass front and mirror see the same "mirror" writing. People can easily read what someone writes on their foreheads, and it is not "mirror" writing. People can choose to observe from another viewpoint.

Because mirror reversal still occurs using only one eye, having two horizontally separated eyes does not affect mirror reversal. Observing mirror reversal while prone, with eyes vertically separated, does not affect mirror reversal.

Mirror reversals are not just verbal reports, because "mirror" writing is difficult to read and looks different from normal writing.

Because mirror reversal occurs even when people cannot perceive the mirror, mirror reversal does not have cognitive rotation around vertical axis. People do not see mirror reversal if they think a mirror is present, but it is not.

2.24. Vision problems

Multiple sclerosis, neglect, and prosopagnosia can cause vision problems {vision problems}.

Cornea can have different curvature radiuses at different orientations around visual axis and so be non-spherical {astigmatism}. Unequal lens curvature causes astigmatism.

Failure to combine or fuse images from both eyes results in double vision {diplopia}.

People can see subjective sparks or light patterns {phosphene} after deprivation, blows, eyeball pressure, or cortex stimulation.

Genetic condition causes retina degeneration {retinitis pigmentosa} and affects night vision and peripheral vision.

People with vision in both eyes can lose ability to determine depth by binocular disparity {stereoblindness}.

Extraocular muscles, six for each eye, can fail to synchronize, so one eye converges too much or too little, or one eye turns away from the other {strabismus}. This can reduce acuity {strabismic amblyopia} {amblyopia}, because image is not on fovea.

2.24.1. Color-vision problems

Partial or complete color-vision loss makes everything light or dark gray, and even dreams lose color.

Left inferior parietal lobe fusiform gyrus damage causes scene to have no color and be light and dark gray {achromatopsia} [Hess et al., 1990] [Nordby, 1990].

Cone pigments can differ in frequency range or maximum-sensitivity wavelength {anomalous trichromacy}. Moderately colorblind people can have three photopigments, but two are same type: two different long-wavelength cones {deuteranomalous trichromacy}, which is more common, or two different middle-wavelength cones {protanomalous trichromacy} [Asenjo et al., 1994] [Jameson et al., 2001] [Jordan and Mollon, 1993] [Nathans, 1999].

8% of men cannot distinguish between red and green {color blindness} {colorblind} {red-green colorblindness}, but can see blue. They also cannot see colors that are light or have low saturation. Dichromats have only two cone types. Cone monochromats can lack two cone types and cannot distinguish colors well. Rod monochromats can have no cones, have complete color blindness, see only grays, and have low daylight acuity.

People can have all three cones but have one photopigment that differs from normal {color-anomalous}, so two photopigments are similar to each other. They typically have similar medium-wavelength cones and long-wavelength cones and cannot distinguish reds, oranges, yellows, and greens.

People can lack medium-wavelength cones, but have long-wavelength cones and short-wavelength cones {deuteranope}, and cannot distinguish greens, yellows, oranges, and reds.

People can lack long-wavelength cones, but have medium-wavelength cones and short-wavelength cones {protanope}, and cannot distinguish reds, oranges, yellows, and greens.

People can lack short-wavelength cones, but have medium-wavelength cones and long-wavelength cones {tritanope}, and cannot distinguish blue-greens, blues, and purples.

2.24.2. Lesions

Brain can have wounded or infected areas {lesion}. If lesion is in right hemisphere, loss is on left visual-field side {contralesional field}. If lesion is in right hemisphere, loss is on right visual-field side {ipsilesional field}.

Mediotemporal (MT) damage causes inability to detect motion {akinetopsia}.

Lateral-geniculate-nucleus damage causes blindness in half visual field {hemianopia} [Celesia et al., 1991].

Removing both temporal lobes makes monkeys fail to recognize objects {Klüver-Bucy syndrome}.

Visual-cortex region can have damage {scotoma}. People do not see black or dark area, but only have no sight [Teuber et al., 1960] [Teuber, 1960].

Visual-nerve damage can cause no or reduced vision in scene regions {visual-field defect}.

Two brain lesions in different places typically cause different defects {double dissociation}.

2.24.3. Blindsight

Cortical-hemisphere-damage blindness affects only half visual field. People with visual-cortex scotoma can point to and differentiate between fast movements or simple objects but say they cannot see them {blindsight}. They can perceive shapes, orientations, faces, facial expressions, motions, colors, and event onsets and offsets [Baron-Cohen, 1995] [Cowey and Stoerig, 1991] [Cowey and Stoerig, 1995] [Ffytche et al., 1996] [Holt, 1999] [Kentridge et al., 1997] [Marcel, 1986] [Marcel and Bisiach, 1988] [Marzi, 1999] [Perenin and Rossetti, 1996] [Pöppel et al., 1973] [Rossetti, 1998] [Stoerig and Barth, 2001] [Stoerig et al., 2002] [Weiskrantz, 1986] [Weiskrantz, 1996] [Weiskrantz, 1997] [Wessinger et al., 1997] [Zeki, 1995].

Blindsight is not just poor vision sensitivity but has no experience [Weiskrantz, 1997].

Blindsight does not require functioning area V1. Vision in intact V1 fields does not cause blindsight [Weiskrantz, 1986]. Brain compensates for visual-cortex damage using midbrain, including superior colliculus, and thalamus visual maps, allowing minimal visual perception but no seeing experience. Right prefrontal cortex has more blood flow. Blindsight uses dorsal pathway and seems different for different visuomotor systems [Milner and Goodale, 1995]. Animals with area V1 damage react differently to same light or no-light stimuli in normal and blindsight regions, with reactions similar to humans, indicating that they have conscious seeing.

Blindsight patients do not have altered thresholds or different criteria about what it means to see [Stoerig and Cowey, 1995].

Properties are:

- Visual acuity decreases by two spatial-frequency octaves.
- Events in blind region can alter attention.
- Color sensitivity is better for red than green.
- Contrast discrimination is less.
- Dark adaptation remains.
- People who cannot see faces can distinguish familiar and unfamiliar faces.
- Complex motion detection is lost. Fast motions, onsets, and offsets can give vague awareness {blindsight type 2}. People with blindsight can detect movement but not recognize object that moved [Morland, 1999].
- Vision reflexes still operate.
- Blindsight patients can be conscious of fast, high-contrast object movements {Riddoch phenomenon}. Retinal output for motion can go to area V5 [Barbur et al., 1993].

People can perceive smells when visual cortex has damage [Weiskrantz, 1997]. People can perceive sounds when visual cortex has damage [Weiskrantz, 1997]. People with parietal lobe damage can use tactile information, though they do not feel touch {numbsense} {blind touch}.

Amnesiacs with medial temporal lobe damage can use non-conscious memory.

2.25. Techniques of studying vision

If an object moves behind a slit, people can faintly glimpse whole object {anorthoscopic perception}. Object foreshortens along motion direction. People can also recognize an object that they see moving behind a pinhole, because memory and perception work together.

People wearing glasses that make everything appear inverted or rotated {visual distortion} {distortion} soon learn to move around and perform tasks while seeing world upside down. Visual distortion adaptation involves central-nervous-system sense and motor neuron coding changes, not sense-organ or muscle changes. Eye, head, and arm position-sensations change, but retinal-image-position sensations do not change. People do not need to move to adapt to visual distortion.

To try to induce ESP, illumination can be all white or pink with no features, and sound can be white noise {ganzfeld} {autoganzfeld}.

Gratings {grating} have alternating dark bars and light bars. Each visual-angle degree has some bar pairs {cycles per degree}. Gratings have cycles per visual-angle degree {spatial frequency}. Gratings {phase} can have relative visual-image positions. Gratings {sine wave grating} can have luminance variation like sine waves, rather than sharp edges.

Figure sets {Mooney figures}, to display at different orientations or inversions, can show ambiguous faces (C. M. Mooney) [1957]. Faces have analytic face features and different configurations, so people typically perceive only half as faces.

At one location, many different stimuli can quickly appear and disappear {rapid serial visual presentation} (RSVP), typically eight images per second.

Three-dimensional graphs {spectrogram} can show time on horizontal axis, frequency on vertical axis, and intensity as blue-to-red color or lighter to darker gray.

Picture pairs {stereogram} can have right-eye and left-eye images, for use in stereoscopes. Without stereoscopes, people can use convergence or divergence {free fusion} to resolve stereograms and fuse images.

If people stare at circle center, circle fades {Troxler test} (Ignaz Troxler) [1804].

Instruments {ophthalmoscope} can allow viewing retina and optic nerve.

2.25.1. Binocular rivalry

If eyes see different images, people see first one image and then the other {binocular rivalry} [Andrews and Purves, 1997] [Andrews et al., 1997] [Blake, 1989] [Blake, 1998] [Blake and Fox, 1974] [Blake and Logothetis, 2002] [Dacey et al., 2003] [de Lima et al., 1990] [Engel and Singer, 2001] [Engel et al., 1999] [Epstein and Kanwisher, 1998] [Fries et al., 1997] [Fries et al., 2001] [Gail et al., 2004] [Gold and Shadlen, 2002] [Kleinschmidt et al., 1998] [Lee and Blake, 1999] [Lehky and Maunsell, 1996] [Lehky and Sejnowski, 1988] [Leopold and Logothetis, 1996] [Leopold and Logothetis, 1999] [Leopold et al., 2002] [Levelt, 1965] [Logothetis, 1998] [Logothetis, 2003] [Logothetis and Schall, 1989] [Logothetis et al., 1996] [Lumer and Rees, 1999] [Lumer et al., 1998] [Macknik and Martinez-Conde, 2004] [Meenan and Miller, 1994] [Murayama et al., 2000] [Myerson et al., 1981] [Parker and Krug, 2003] [Pettigrew and Miller, 1998] [Polonsky et al., 2000] [Ricci and Blundo, 1990] [Sheinberg and Logothetis, 1997] [Tong and Engel, 2001] [Tong et al., 1998] [Wilkins et al., 1987] [Yang et al., 1992].

In binocular rivalry, vision sees one image {dominant image} with more contrast, higher spatial frequency, and/or more familiarity for more time.

If eyes see different images and briefly presented stimulus follows one image, that image is less intense and people see other image more {flash suppression} [Kreiman et al., 2001] [Sheinberg and Logothetis, 1997] [Wolfe, 1984] [Wolfe, 1999].

3. Perceptual properties

People can distinguish 150 to 200 main colors and seven million different colors {color vision}, by representing the light intensity-frequency spectrum and separating it into categories. Different color-receptor-system time constants cause color.

Three coloring methods are coloring points, coloring areas, or using separate color overlays. Mind colors areas, not points or overlays, because area coloring is discrete and efficient.

Surfaces can be transparent, translucent (semi-reflective), or opaque (reflective) {opacity}. For each wavelength, a percentage {absorbance} of impinging light remains in the surface. Surface transmits or reflects the rest. For each wavelength, a percentage {reflectance} of impinging light reflects from surface. Surface transmits or absorbs the rest. Reflectance changes at object boundaries are abrupt [Land, 1977]. Color depends on both illumination and surface reflectance [Land, 1977]. Comparing surface reflective properties to other or remembered surface reflective properties results in color.

Because color depends on source illumination and surface reflectance, no surface or object physical property corresponds to color. Colors are are not essential to object identity.

People's vision processes are similar, so everyone's vision perceptions are similar. All people see the same color spectrum, with the same colors and color sequence. Colorblind people have consistent but incomplete spectra.

Color can have no definite depth {aperture color}, such as at a hole in a screen.

If eyes completely adapt to dark, people see gray {brain gray} {eigengrau}.

Light polarization can affect sight slightly {Haidinger brush}.

Light is only electromagnetic waves. Matter and energy cannot cause color, though experience highly correlates with physical quantities.

3.1. Vertebrates, mammals, and primates

Non-mammal vertebrates have one cone type, have no color opponent process, and detect colors from purples to reds, with poorer discrimination than mammals.

Mammals have two cone types. Mammals have short-wavelength receptor and long-wavelength receptor. For example, dogs have receptor with maximum sensitivity at 429 nm, which is blue for people, and receptor with maximum sensitivity at 555 nm, which is yellow-green for people. Mammals can detect colors from purples to reds, with poorer discrimination than people. With two cone types, mammals have only one color opponency, yellow-blue. (Perhaps, mammals cannot see phenomenal colors because color sensations require two opponent processes.)

Primates have three cone types, and two opponent processessee, and can discriminate colors well.

3.2. Color range

Colors range continuously from red to scarlet, vermilion, orange, yellow, chartreuse, green, spring green, cyan, turquoise, blue, indigo (ultramarine), purple, magenta, crimson, and back to red. Scarlet is red with some orange. Vermilion is half red and half orange. Chartreuse is half yellow and half green. Cyan is half green and half blue. Turquoise is blue with some green. Indigo is blue with some red. Purple is blue with more red. Magenta is half blue and half red. Crimson is red with some blue.

Hue, brightness, and saturation ranges make all perceivable colors {gamut}. Perceivable-color range is greater than three-primary-color additive-combination range. However, allowing subtraction of red makes color gamut.

Color can have light surround and appear to reflect light {related color}. Color can have dark surround and appear luminous {unrelated color}. Brown can appear only when other colors are present.

Gray can appear only when other colors are present. If background is white, gray appears black. If background is black, gray appears white.

3.2.1. Colors

The eleven fundamental color categories are white, black, red, green, blue, orange, yellow, pink, brown, purple, and gray [Byrne and Hilbert, 1997] [Wallach, 1963].

Major colors are red, yellow, green, and blue. Yellow is red and green. Green is yellow and blue. Minor colors are orange, chartreuse, cyan, and magenta. Orange is red and yellow. Chartreuse is yellow and green. Cyan is green and blue . Magenta is red and blue. Halftones are between major and minor color categories: red-orange {vermilion}, orange-yellow, yellow-chartreuse, chartreuse-green, green-cyan {spring green}, cyan-blue {turquoise}, blue-purple {indigo} {ultramarine}, indigo-magenta or blue-magenta {purple}, and magenta-red {crimson}.

White, gray, and black have no hue {achromatic} and have color purity zero.

White is relatively higher in brightness than adjacent surfaces. Adding white to color makes color lighter. However, increasing colored-light intensity does not make white. When light is too dim for cones, people see whites, grays, and blacks. When light is intense enough for cones, people see whites, grays, and blacks if no color predominates. Spectral colors have complementary colors. Color and complementary color mix to make white, gray, or black. Two spectral colors mix to make intermediate color, which has a complementary color. Mixing two spectral colors and intermediate-color complementary color makes white, gray, or black.

Black is relatively lower in brightness than adjacent surfaces. Black is not absence of visual sense qualities but is a color.

Gray is relatively the same brightness as adjacent surfaces.

Red light is absence of blue and green, and so is absence of cyan, its additive complementary color. Red pigment is absence of green, its subtractive complementary color. Spectral red cannot be a mixture of other colors. Pigment red cannot be a mixture of other colors. Red is alerting color. Red is warm color, not cool color. Red is light color. Red mixes with white to make pink. Spectral red blends with spectral cyan to make white. Pigment red blends with pigment green to make black. Spectral red blends with spectral yellow to make orange. Pigment red blends with pigment yellow to make brown. Spectral red blends with spectral blue to make purples. Pigment red blends with pigment blue to make purples. People do not see red as well at farther distances. People do not see red as well at visual periphery. Red has widest color range because reds have longest wavelengths and largest frequency range. Red can fade in intensity to brown then black. Perhaps, red evolved to discriminate food.

Blue light is absence of red and green, so blue is absence of yellow, its additive complementary color. Blue pigment is absence of red and green, so blue is absence of orange, its subtractive complementary color. Spectral blue cannot be a mixture of other colors. Pigment blue cannot be a mixture of other colors. Blue is calming color. Blue is cool color, not warm color. Blue is light color. Blue mixes with white to make pastel blue. Spectral blue blends with spectral yellow to make white. Pigment blue blends with pigment yellow to make black. Spectral blue blends with spectral green to make cyan. Pigment blue blends with pigment green to make dark blue-green. Spectral blue blends with spectral red to make purples. Pigment blue blends with pigment red to make purples. People see blue well at farther distances. People see blue well at visual periphery. Blue has narrow wavelength range. Perhaps, blue evolved to tell when sky is changing or to see certain objects against sky. Teal is less saturated cyan.

Green light is absence of red and blue, and so magenta, its additive complementary color. Green pigment is absence of red, its subtractive complementary color. Spectral green can mix blue and yellow. Pigment green can mix blue and yellow. Green is neutral color in alertness. Green is cool color. Green is light color. Green mixes with white to make pastel green. Spectral green blends with spectral magenta to make white. Pigment green blends with pigment magenta to make black. Spectral green blends with spectral orange to make yellow. Pigment green blends with pigment orange to make brown. Spectral green blends with spectral blue to make cyan. Pigment green blends with pigment blue to make dark blue-green. People see green OK at farther distances. People do not see green well at visual periphery. Green has wide wavelength range. Perhaps, green evolved to discriminate fruit and vegetable ripening.

Yellow light is absence of blue, because blue is its additive complementary color. Yellow pigment is absence of indigo or purple, its subtractive complementary color. Spectral yellow can mix red and green. Pigment yellow cannot be a mixture of other colors. Yellow is neutral color in alertness.

Yellow is warm color. Yellow is light color. Yellow mixes with white to make pastel yellow. Spectral yellow blends with spectral blue to make white. Pigment yellow blends with pigment blue to make green. Spectral yellow blends with spectral red to make orange. Pigment yellow blends with pigment red to make brown. Olive is dark low-saturation yellow (dark yellow-green). People see yellow OK at farther distances. People do not see yellow well at visual periphery. Yellow has narrow wavelength range.

Spectral orange can mix red and yellow. Pigment orange can mix red and yellow. Orange is slightly alerting color. Orange is warm color. Orange is light color. Orange mixes with white to make pastel orange. Spectral orange blends with spectral blue-green to make white. Pigment orange blends with pigment blue-green to make black. Spectral orange blends with spectral cyan to make yellow. Pigment orange blends with pigment cyan to make brown. Spectral orange blends with spectral red to make light red-orange. Pigment orange blends with pigment red to make dark red-orange. People do not see orange well at farther distances. People do not see orange well at visual periphery. Orange has narrow wavelength range.

Spectral purple can mix blue and red. Pigment purple has red and so is purple. Purple is calming color. Purple is cool color. Purple is light color. Purple mixes with white to make pastel purple. Spectral purple blends with spectral yellow-green to make white. Pigment purple blends with pigment yellow-green to make black. Spectral purple blends with spectral red to make purples. Pigment purple blends with pigment red to make purples. People see purple well at farther distances. People see purple well at visual periphery. Purple has narrow wavelength range. Purple can fade in intensity to dark purple then black.

Pigment brown can mix red, yellow, and green. Brown is commonest color but is not spectral color. Brown is like dark orange pigment or dark yellow-orange. Brown color depends on contrast and surface texture. Brown is not alerting or calming. Brown is warm color. Brown is dark color. Brown mixes with white to make pastel brown. Pigment brown blends with other pigments to make dark brown or black. People do not see brown well at farther distances. People do not see brown well at visual periphery. Brown is not spectral color and has no wavelength range.

Purples come from mixing red and blue. They have no green, to which they are complementary. Purples are non-spectral colors, because reds have longer wavelengths and blues have shorter wavelengths. Purple is low-saturation magenta.

3.2.2. Pure colors

Blue, green, and yellow have definite wavelengths at which they are pure, with no other colors. Red has no definite wavelength at which it is pure. Red excites mainly long-wavelength receptor. Yellow is at long-wavelength-receptor maximum-sensitivity wavelength. Green is at middle-wavelength-receptor maximum-sensitivity wavelength. Blue is at short-wavelength-receptor maximum-sensitivity wavelength.

Colors from light sources cannot add to make red or to make blue. Colors from pigment reflections cannot add to make red or to make blue.

3.3. Color change

Colors changes with illumination intensity, illumination spectrum, background surface, adjacent surface, distance, and viewing angle. Different people vary in what they perceive as unique yellow, unique green, and unique blue. The same person varies in what they perceive as unique yellow, unique green, and unique blue.

Colors respond differently as hue changes. Reds and blues change more slowly than greens and yellows.

3.4. Color constancies

Vision maintains constancies: size constancy, shape constancy, color constancy, and brightness constancy {constancy}. Size constancy is accurate and learned.

Sight tries to keep surface colors constant {color constancy}. Lower luminance makes more red or green, because that affects red-green opponency more. Higher luminance makes more yellow or blue, because that affects blue-yellow opponency more.

3.5. Color properties

Properties {determinable property} can be about categories, such as blue. Properties {determinate property} can be about specific things, such as unique blue, which has no red or green.

Colors can be relatively warm or cool. Black-body-radiator spectra center on red at 3000 K, blue at 5000 K, and white at 7000 K. Light sources have radiation surface temperature {color temperature} comparable to black-body-radiator surface temperature. However, people call blue cool and red warm, perhaps because water and ice are blue and fires are red, and reds seem to have higher energy output. Warm pigments have more saturation and are lighter than cool pigments. White, gray, and black, as color mixtures, have no net temperature.

Blue objects appear to go farther away and expand, and red objects appear to come closer and contract, because reds appear lighter and blues darker.

Color can have shallow or deep depth. Yellow is shallow. Green is medium deep. Blue and red are deep. Perhaps, depth relates to color opponent processes. Red and blue mainly excite one receptor. Yellow and green mainly excite two receptors. Yellow mixes red and green. Green mixes blue and yellow.

Yellow is the brightest color, comparable to white. In both directions from yellow, darkness grows {color lightness} . Colors darken from yellow toward red. Colors darken from yellow toward green and blue. Green is lighter than blue, which is comparable to black.

Dark colors are sad and light colors are glad, because dark colors are less bright and light colors are more bright.

Psychologically, red is alerting color. Green is neutral color. Blue is calming color.

Blue light has shorter wavelength and has more refraction and scattering by atoms. Long-wavelength and medium-wavelength cones have similar wavelength sensitivity maxima, so scattering and refraction are similar. Fovea has no short-wavelength cones, for better length precision.

Age gradually yellows eye lenses, and vision becomes more yellow.

3.6. Qualia

Systems that can perform same visual functions that people perform can have no qualia {absent qualia}. Perhaps, machines can duplicate neuron and synapse functions, as in the China-body system [Block, 1980], and so do anything that human visual system can do. Presumably, system physical states and mechanisms, no matter how complex, do not have or need qualia. System has inputs, processes, and outputs. Perhaps, such systems can have qualia, but complexity, large scale, or inability to measure prevents people from knowing.

Perhaps, hue can be not any combination of red, blue, green, or yellow {alien color}.

3.6.1. Inverted Earth

Planets {Inverted Earth} {inverted qualia} can have complementary colors of Earth things [Block, 1990]. For same things, its people experience complementary color compared to Earth-people color experience. However, Inverted-Earth people call what they see complementary color names rather than Earth color names, because their vocabulary is different. When seeing tree leaves, Inverted-Earth people see magenta and say green.

If Earth people go to Inverted Earth and wear inverting-color lenses, they see same colors as on Earth and call colors same names as on Earth. When seeing tree leaves, they see green and call them green, because they use Earth language.

If Earth people go to Inverted Earth and do not wear inverting-color lenses, they see complementary colors rather than Earth colors and call them Earth names for complementary colors. However, if they stay there, they learn to use Inverted-Earth language and call complementary colors Inverted-Earth names, though phenomena remain unchanged. When seeing tree leaves, they see magenta and say green. Intentions change though objects remain the same. Therefore, phenomena are not representations.

Intentions probably do not change, because situation requires no adaptations. The representation is fundamentally the same.

Perhaps, qualia do change.

3.6.2. Inverted spectrum

Perhaps, spectrum can invert, so people see short-wavelength light as red and long-wavelength light as blue {inverted spectrum}. Perhaps, phenomena and experiences can be their opposites without affecting moods, emotions, body sensations, perceptions, cognitions, or behaviors. Subject experiences differently, but applies same functions as other people, so subject reactions and initiations are no different than normal. This can start at birth or change through learning and maturation. Perhaps, behavior and perception differences diminish over time by forgetting or adaptation.

Seemingly, for inverted spectrum, representations are the same, but inverted phenomena replace phenomena. Functions or physical states remain identical, but qualia differ. If phenomena involve representations, inverted spectra are not metaphysically possible. If phenomena do not involve representations, inverted spectra are metaphysically possible.

Inverted spectra are not necessarily conceptually possible, because they can lead to internal contradictions. Colors do not have exact inversions, because colors mix differently, so no complete and consistent color inversion is possible.

3.7. Gestalt

Perception must separate object figure from background {ground}, using Gestalt laws [Ehrenfels, 1891].

Vision finds simplest possible percept, which has internal consistency and regularity {pragnans}.

Vision tends to perceive incomplete or occluded figures as wholes {closure law} {law of closure}. Closed contour indicates figure.

Vision groups features doing same thing {common fate}, such as moving in same direction or moving away from point.

Vision groups two features that touch or that happen at same time {connectedness} {law of connectedness}.

Vision tends to perceive enclosed region as figure {enclosedness} {law of enclosedness} {surroundedness}. Surrounded region is figure, and surrounding region is ground.

Vision perceives organization that interrupts fewest lines or that lies on one contour {good continuation} {law of good continuation}. Smooth lines, with no sharp angles, are figure parts. Regions with fewer continuous lines, fewer angles, and fewer angle differences are figures. For example, the good-continuation law reflects probability that aligned edges belong to same object.

Vision groups two parallel contours {parallelism}. Region parallel contours are figure parts, and non-parallel contours are ground parts. Surfaces have periodic structure that can model periodic structures.

Adjacent features are figure parts {proximity} {law of proximity}.

Vision finds image boundaries, to make perceptual regions, by angles, lines, and distances {segregation} {law of segregation} {differentiation} {law of differentiation}.

Similar shape, color, and size parts go together {similarity} {law of similarity}.

Vision groups symmetrical contours {symmetry law}. Symmetrical region is figure, and asymmetrical region is ground. Symmetrical closed region is figure.

Vision groups features that change simultaneously {synchrony}, even if features move in different directions and/or at different speeds.

3.7.1. Gestalt laws

Figures have three-dimensional representations or forms {gestalt} built innately by vision, by analyzing stimulus interactions. Gestalt needs no learning.

Finding stimulus relations or applying organizational laws {insight} allows recognizing figures, solving problems, and performing similar mental tasks. Related gestalt laws can conflict, and they have different relative strengths at different times. Grouping laws depend on figure-ground relationship, proximity, similarity, continuity, closure, connectedness, and context. Laws {gestalt law} {grouping rule} {Gestalt grouping rule} can replace less-organized patterns with emphasized, complete, or adequate patterns. Gestalt laws are minimizations. Gestalt laws are assumptions about which visual-field parts are most likely to belong to which object.

3.7.2. Figure and ground

Perception must separate object {figure} from background, using Gestalt laws. Regions with one color are figures. Many-colored regions are ground. Smaller region is figure, and nearby larger region is ground.

Edges separate figure and ground. Lateral inhibition distinguishes and sharpens boundaries.

Both figure and ground are homogeneous regions. Surfaces recruit neighboring similar surfaces to expand homogeneous regions by wave entrainment.

Vision separates figure and ground by detecting edges and increasing homogeneous regions, using constraint satisfaction [Crane, 1992].

3.8. Illusions

Illusions {illusion} are perceptions that differ from actual metric measurements. Brain uses rules to interpret sense signals, but rules can have contradictions or ambiguities. Vision sees bent lines, shifted lines, different lengths, or different areas, rather than line or area physical properties. Visual illusions are typically depth-perception errors [Frisby, 1979] [Gregory, 1972] [von der Heydt et al., 1984] [Kanizsa, 1979] [Peterhans and Heydt, 1991].

Illusion, hallucination, and perception sense qualities do not differ. Mind typically does not notice illusions.

Illusions can depend on brightness differences, sound-intensity differences, or line-length and line-spacing differences {Craik-Cornsweet illusion}. Finding differences explains Weber's law and why just noticeable difference increases directly with stimulus magnitude.

Figures can have features that randomly appear and disappear, because neural channels differ for movement and position. Horizontal and vertical lines with gaps at intersections {Hermann grid} have gray circles, in white spaces where four corners meet, that appear and disappear. Rotating spiral snakes (Akiyoshi Kitaoka) have spirals, which make faint opposite spirals appear to rotate. Thatcher illusion has smile and eye corners up or down (Peter Thompson).

Illusions can have two forms, and people see mostly one {perceptual dominance}, then other. Vase-and-face illusion switches between alternatives. Illusions with two forms {bistable illusion}, like Necker cube, have two forms almost equal in perceptual dominance.

When two objects have interchangeable features, and time or attention is short, mind can switch features to wrong object {conjunction error}.

People can experience paradox perceptually while knowing its solution conceptually. Pictures are essentially paradoxical. Minds can combine two features, for example, color and shape, and report perceiving objects that are not in scenes {illusory conjunction} {conjunction}.

Perhaps, there are color illusions due to illumination intensity, illumination spectrum, background surface, adjacent surface, distance, and viewing angle. Human color processing cannot always process the same way or to the same result. Color names and categories have some correspondence with other animals, infants, and cultures, but vary among scientific observers and by introspection.

Music can cause illusions.

3.8.1. Aftereffect

After concentrating on object and then looking at another object, sense qualities opposite to, or shifted away from, original appear {aftereffect} (CAE) [Blake, 1998] [Blake and Fox, 1974] [Dragoi et al., 2000] [He et al., 1996] [He et al., 1998] [He and MacLeod, 2001] [Koch and Tootell, 1996] [Montaser-Kouhsari et al., 2004].

Aftereffects appear because sense channels for processing color and orientation overlap {built-in theory} or because separate mechanisms for processing color and orientation overlap during adaptation period {built-up theory}.

Perhaps, CAEs reflect brain self-calibration. Orientation-specific adaptation is in area V1 or V2.

After observing bright light or image with steady gaze, image can persist {afterimage} [Hofstötter et al., 2003]. For one second, afterimage is the same as positive image. Then afterimage has opposite color or brightness {negative afterimage}. Against white ceiling, afterimage appears black. Colored images have complementary-color afterimages. Intensity is the same as image {positive afterimage} if eyes close or if gaze shifts to black background. Afterimage size, shape, brightness, and location can change {figural aftereffect}.

Horizontal and vertical gratings cause opposite aftereffect {orientation-dependent aftereffect}, even if not perceived. Orientation-specific color aftereffects can appear without perception {McCullough effect}. McCullough effect does not transfer from one eye to the other.

After observing a pattern at an orientation, mind sees vertical lines tilt in opposite direction {tilt aftereffect}.

Background can seem to move after observer stops moving {motion aftereffect}.

Alternating patterns and prolonged sense stimulation can cause distortions that depend on adapting-field and test-field stripe orientations {contingent perceptual aftereffect}.

Aftereffects also appear after prolonged stimulation by curved lines. Distortions associated with converging lines do not change with different brightness or line thickness.

CAEs do not necessarily decay during sleep and can last for days.

3.8.2. Ambiguous figures

Figures {ambiguous figure} can have two ways that non-vertical and non-horizontal lines can orient or have two ways to choose background and foreground regions. In constant light, observed ambiguous-figure surface-brightness changes as perception oscillates between figures [Gregory, 1966] [Gregory, 1986] [Gregory, 1987] [Gregory, 1997] [Seckel, 2000] [Seckel, 2002].

Ambiguous figures (Jastrow) can have duck beaks and rabbit ears {duck-rabbit illusion}.

Vases with profiles of symmetrical faces (Edgar Rubin) can make an ambiguous figure {vase and two faces illusion} {Rubin vase}. Central vase has profiles that are symmetrical faces (Edgar Rubin).

Old crone with black hair facing young girl can make an ambiguous figure {Salem witch and girl illusion}.

Other ambiguous figures are eskimo-little girl seen from back, father-son, skull-two dancers, and vase-goblet.

3.8.3. Color illusions

Color can cause color-contrast illusions and color and brightness illusions.

Assimilation illusions have background effects that group same color points differently.

Fading dot illusion has a green disk with blue dot in center, which fades with continued looking.

Munker illusion has blue vertical bars with same-color rectangle behind bars or adjacently and translucently in front of bars, looking like different colors.

Neon disk has an asterisk with half-white and half-red bars, which spins.

Stroop effect has the word green in red, the word red in green.

Gray patches surrounded by blue are slightly yellow {color contrast effect}. Black is not as black near blue or purple.

Mind can perceive transparency when observing different-color split surfaces {color scission}.

Blue and green appear closer {color stereo effect}. Red appears farther away.

Lighter color contours inside darker color contours spread through interiors {watercolor effect}.

In dark, blues seem brighter than reds {Purkinje shift}. In day, reds seem brighter than blues.

Light and dark checkerboards can have light-color dots at central dark-square corners, making curved square sides and curved lines along square edges {flying squirrel illusion}, though lines are really straight (Kitaoka).

3.8.4. Contrast illusions

Contrast can cause illusions.

Adelson illusion has grid of lighter and darker squares, making same-gray squares look different.

Craik-O'Brien-Cornsweet illusion has lighter rectangle beside darker rectangle, making contrast enhancement at boundary.

Mach bands have boundaries with enhanced contrast.

Simultaneous brightness contrast illusions have same-gray squares in white or black backgrounds, looking like different grays.

White illusion has black vertical bars with same-gray rectangle behind bars and adjacently and translucently in front of bars, looking like different grays.

Minds perceive darker objects as heavier than lighter ones {empty suitcase effect}.

Lighter areas have apparently greater size than same-size darker areas {irradiation}.

Illusions {Pepper's ghost} {stage ghost} {camera lucida} can depend on brightness differences. Part-reflecting mirrors can superimpose images on objects that people see through glass. Brightening one image while dimming the other makes one appear as the other disappears. If equally illuminated, both images superimpose and are transparent.

Illusory people perceptions {ghost} can be partially transparent and speak.

3.8.5. Depth illusions

Size and depth can make illusions.

People can see logically paradoxical objects {impossible triangle} {impossible staircase} (Maurits C. Escher).

Impossible triangles (Maurits C. Escher) can make illusions {Kanizsa illusion} {Kanizsa triangle}.

Wire cubes at angles can make illusions {Necker cube}.

Impossible stairs can make illusions {Schroder stairs}.

Other size and depth illusions are Ames room (Adelbert Ames), corridor illusion, impossible waterfall (Maurits C. Escher), size distortion illusion, and trapezoidal window (Adelbert Ames).

3.8.6. Imaginary-line illusions

Imagined lines can cause illusions. Mind can extend contours to places with no reflectance difference {illusory contour}.

Illusory circle has a small space between horizontal and vertical lines that do not meet, making a small circle.

Illusory triangle has solid figures with cutouts that make angles in needed directions, which appear as corners of triangles with complete sides.

Illusory square has solid figures with cutouts that make angles in needed directions, which appear as corners of squares with complete sides.

3.8.7. Geometric illusions

Geometry, size, length, and curvature line or edge distortions can make illusions.

Lines with inward-pointing arrowheads and adjacent lines with outward-pointing arrowheads appear to have different lengths {Müller-Lyer illusion}.

If railroad tracks and ties lead into distance, and two horizontal bars, even with different colors, are at different distances, farther bar appears longer (Mario Ponzo) [1913] {Ponzo illusion}. Perhaps, line tilt, rather than depth perception, causes Ponzo illusion. Perhaps, line tilt, rather than depth perception, causes Ponzo illusion.

Vertical lines with equally spaced parallel line segments at 45-degree angles can make illusions {Zollner illusion}.

Ehrenstein illusion has radial lines with circle below center and square above center, making circle and square lines change alignment.

Radial rays with two horizontal lines can make illusions {Hering illusion}.

Line segments radiating from central imaginary circle {radial lines illusion} make center circle appear brighter. If center circle is black, it looks like background. If center circle has color, it appears brighter and raised {anomalous brightness}. If center circle is gray disk, it appears gray but shimmers {scintillating luster}. If center circle has color and background is black, center circle appears blacker {anomalous darkness}. If center circle has color and gray disk, center circle shimmers gray with complementary color {flashing anomalous color contrast}.

An illusion {café-wall illusion} has a vertically irregularly spaced black squares and white squares grid, making horizontal lines appear tilted.

Distorted squares illusion has squares in concentric circles, making tilted lines.

A vertical line segment in a tilted square frame appears to tilt oppositely {rod and frame illusion}, a late-visual-processing pictorial illusion.

If a rectangle is left of midline, with one edge at midline, rectangle appears horizontally shorter, and midline line segment appears to be right of midline {Roelof's effect} {Roelof effect}. If a rectangle is left of midline, with edge nearer midline left of midline, rectangle appears horizontally shorter, and rectangle appears closer to midline.

Men with sunglasses illusion (Akiyoshi Kitaoka) has alternating color-square grid with two alternating vertical or horizontal dots at corners, making vertical and horizontal lines tilted.

Midorigame or green turtle (Akiyoshi Kitaoka) has a grid with slightly tilted squares in one direction and a center grid with squares slightly tilted in other direction, making vertical and horizontal lines tilted.

Poggendorf illusion has two vertical lines with diagonal line that goes behind space between lines, and two vertical lines with diagonal line that goes behind space between lines and dotted line on one side, making behind look not aligned.

Central circle with vertical stripes surrounded by annulus with stripes angled to left appears to have stripes tilted to right {simultaneous tilt illusion}, an early visual processing illusion.

Medium-size circle surrounded by smaller circles appears larger than same-size circle surrounded by larger circles {Ebbinghaus illusion} {Titchener circles illusion}, a late-visual-processing pictorial illusion.

Frazier spiral has concentric circles that look like a spiral in a spiraling background.

If small and large object both have same weight, small object feels heavier in hand than large object {size-weight illusion}. People feel surprise, because larger weight is lighter than expected.

Moon or Sun apparent size varies directly with nearness to horizon {Moon illusion}, until sufficiently above horizon. On horizon, Moon is redder, hazier, lower contrast, and fuzzier edged and has different texture. All these factors affect perceived distance. Horizon Moon dominates and elevates scene, but scene seems lower when Moon is higher in sky. Horizon Moon, blue or black sky, and horizon are apparently at same place. Risen Moon appears in front of black night sky or blue day sky, because it covers blue or black and there is no apparent horizon. Moon illusion and other perspective illusions cause visual-brain topographic image to enlarge or shrink, whereas retinal image is the same.

3.8.8. Motion Illusions

Motions or lack of motions can cause illusions.

In homogeneous backgrounds, a single object appears to move around {autokinetic effect} {keyhole illusion} [Zeki et al., 1993].

If line or spot is moving, and another line or spot flashes at same place, the other seems behind first {flash-lag effect} [Eagleman and Sejnowski, 2000] [Krekelberg and Lappe, 2001] [Nijhawan, 1994] [Nijhawan, 1997] [Schlag and Schlag-Rey, 2002] [Sheth et al., 2000]. Flashed object seems slower than moving object.

Rotating two-dimensional objects makes them appear three-dimensional {kinetic depth effect} [Zeki et al., 1993].

Alternating visual-stimulus pairs show apparent movement at special times and separations {Korte's law} [Zeki et al., 1993].

After continuously observing moving objects, when movement stops, stationary objects appear to move {motion aftereffect}.

If screen has stationary color spots and has randomly moving complementary-color spots behind them, mind sees stationary spots first, then does not see them, then sees them again, and so on {motion-induced blindness} [Bonneh et al., 2001].

Spokes in turning wheels seem to turn in direction opposite from real motion {wagon-wheel illusion} [Gho and Varela, 1988] [Wertheimer, 1912] [Zeki et al., 1993].

If people view scenes with flows, when they look at stationary scenes, they see flow {waterfall illusion}. Waterfall illusion can be a series of still pictures [Cornsweet, 1970].

Experimenter taps sharp pencil five times on wrist, three times on elbow, and two times on upper arm, while subject is not looking {cutaneous rabbit}. It feels like equal steps up arm [Geldard and Sherrick, 1972].

In zero-gravity environments, because eyes shift upward, objects appear to be lower than they actually are {zero-gravity illusion}.

3.9. Theories about vision

Perhaps, physical and phenomenological are different visual-appearance types {modes of presentation} {presentation modes}, with different principles and properties. However, how can people know that both vision modes are about same feature or object or how modes relate.

Perhaps, motor behavior determines visual perception {motor theory of perception}. However, eye movements do not affect simple visual sense qualities.

Perhaps, visual phenomena require concepts {phenomenal concept}. Phenomenal concepts are sensation types, property types, quality relations, memory indexes, or recognition principles. Phenomenal concepts refer to objects, directly or indirectly, by triggering thought or memory. However, if physical concepts are independent of phenomenal concepts, physical knowledge cannot lead to phenomenal concepts.

Perhaps, in response to stimuli, people have non-physical inner images {sense-datum}. Physical objects cause sense data. Sense data are representations. Mind introspects sense data to perceive colors, shapes, and spatial relations. For example, perceived colors are relations between perceivers and sense data and so are mental objects. However, sense data are mental objects, but brain, objects, and neural events are physical, and non-physical inner images cannot reduce to physical events.

Perhaps, coordination among sense and motor systems builds visual information structures {sensorimotor theory of vision}. Sense input and motor output have relations {sensorimotor contingency laws}. Body, head, and eye movements position sensors to gather visual information and remember semantic scene descriptions. Objects have no internal representations, only structural descriptions. Vision is activity, and visual perception depends on coordination between behavior and sensation {enactive perception} [Noë, 2002] [Noë, 2004] [O'Regan, 1992] [O'Regan and Noë, 2001]. However, perception does not require motor behavior.

3.9.1. Theories about color

Three coordinates can define all colors that humans can perceive {trichromacy} {trichromatic vision} {trichromatic theory of color vision} {Young-Helmholtz theory}. Humans have three photopigments in three different cone cells that provide the three coordinates. Trichromatic vision is only in Old World monkeys, apes, and humans.

3.9.1.1. Physical theories about color

Perhaps, color relates to physical objects, events, or properties {color realism} {color objectivism}.

Perhaps, color is identical to a physical property {color physicalism}, such as surface spectral reflectance distribution {reflectance physicalism}.

Perhaps, colors are independent of subject and condition. Mental processes allow access to physical colors.

Perhaps, colors represent physical properties {color representationalism}.

Perhaps, colors are objective non-relational physical-object properties and are describable in physical terms {physicalism}. For example, physical colors are surface-reflectance ratios. Object surface color remains almost constant during brightness and spectrum changes, because surface reflectances stay constant. Because objects with different surface reflectances can cause same color, physical colors are disjunctions of surface reflectances. However, experience does not provide information about surface reflectances or other physical properties.

Perhaps, perceived colors are physical-object properties or brain states experienced in space {projectivist theories} {projectivism}. However, mental locations are not physical locations. Mental properties cannot be physical properties, because mental states differ from objects.

Perhaps, vision can compare blue, red, and green surface-reflectance ratios between image segments to determine color {retinex theory}. Background brightness is ratio average. Surface neutral colors depend on blue, red, and green reflectance ratios [Land, 1977]. However, vision does not use local or global brightness or reflectance averages.

3.9.1.2. Mental theories about color

Perhaps, things have no color {color eliminativism}, and color is only in mind.

Perhaps, colors are mental properties, events, or processes {color subjectivism}.

Perhaps, colors are mental properties of mental objects {sense-datum}. Perhaps, colors are perceiver mental processes or events {adverbialism}.

Perhaps, colors are only things that dispose mind to see color {color dispositionalism}.

Perhaps, experience has color content {color intentionalism}, which provides information about surface color.

Perhaps, humans know colors, essentially, by experiencing them {doctrine of acquaintance}, though they can also learn information about colors.

Perhaps, colors are identical to mental properties that correspond to color categories {corresponding category constraint}.

Perhaps, perceived colors are representations {intentionalist theories} {intentionalism and vision}, with no qualitative properties. However, afterimages have colors but do not represent physical objects.

Perhaps, colors have mental qualitative properties {mental color}. Mental colors are what it is like for perceivers to have color consciousness. However, mental colors can have no outside physical basis, whereas experienced colors correlate with physical quantities.

3.9.1.3. Physical and mental theories about color

Perhaps, colors depend on subject and physical conditions {color relationism} {color relativism}.

Perhaps, humans perceive real properties that cause phenomenal color.

Perhaps, perceived color states are relations between perceivers and physical objects {adverbialist theories} {adverbialism} and are neural states, not non-physical mental states. However, experiences do not seem to be relations.

Perhaps, colors are dispositions of physical-object properties to produce visual color states {dispositionalism}. Physical properties dispose perceiver to discriminate and generalize among colors. Colors have no mental qualities. Alternatively, physical-object properties dispose perceivers to experience what it is like to experience color physical properties. Mental qualities allow knowing qualitative similarities among colors. However, experienced colors do not look like dispositions.

How can colors be in mind but appear in space? Subjectivism cannot account for the visual field. Objectivism cannot account for the color facts.

Differences among objective object and physical properties, subjective color processing, and relations among surfaces, illumination, background, viewing angle and distance do not explain perceived color differences {explanatory gap}.

3.9.1.4. Other theories about color

Perhaps, colors depend on action {color enactivism}.

Perhaps, colors depend on required functions {color functionalism}.

Perhaps, colors depend on natural selection requirements {color selectionism}. Perhaps, different species classify colors differently, because they inhabit different niches {adaptivism}. Perhaps, perceived colors are adaptive relations between objects and color experiences, rather than just categories about physical surfaces. However, experiences are mostly about physical quantities.

4. Relations to other senses

Vision and hearing share same perceptual space.

Hearing has higher energy level than vision.

Hearing has longitudinal mechanical waves, and vision has transverse electric waves. Hearing uses wave phase differences, but vision does not.

Noise sound and white color are similar in that they involve multiple frequencies.

Hearing has ten-octave frequency range, and vision has one-octave frequency range.

Hearing hears multiple frequencies, but vision reduces to one quality. Vision mixes sources and frequencies into one sensation, but hearing can detect more than one source and frequency from one location.

Hearing is silent from most spatial locations, but vision displays information from all scene locations.

Hearing can have interference from more than one source, but vision can have interference from only one source.

Hearing has sound attack and decay, but vision is so fast that it has no temporal properties.

Touch coordinates with vision. Touch provides information about eyes. Vision is at eye body surface, but brain feels no touch there.

Temperatures relate to colors because warm colors expand and cool colors contract.

Vision coordinates with kinesthesia.

High-intensity vision is painful.

Vision has no relations to smell or taste.

5. Color sensations

Vision sees color brightness (related to intensity), hue (related to frequency), and saturation (related to frequency distribution).

Colors have a circular color range, from reds, through greens, through blues, through purples, back to reds.

Colors vary continuously over the color range, but have specifiic categories: white, gray, black, red, orange, yellow, green, blue, purple.

People see same basic colors, whether language has rudimentary or sophisticated color vocabulary. Fundamental sense qualities are innate and learned. However, people can learn color information from environment and experiences.

Colors mix/synthesize to make one resultant color.

Colors have brightness. Brightness depends on photon number per second. Light intensity/brightness does not affect frequency/hue, or vice versa. Hue affects saturability.

Colors can have warm, neutral, or cool color temperature.

Colors can have receding, still, or approaching radial activity.

Colors can have low, medium, or high salience.

Colors can have light, medium, or dark color lightness.

Colors can have sparse, medium, or dense spatial distribution/density/spacing.

Vision always has viewpoint, which always changes.

6. Color descriptors

Vision perceives color brightness, temperature, and lightness.

Vision perceives surfaces at distances along radal directions.

Vision has classes/categories for colors, features, objects, events, scenes, and space.

7. Spatiotemporal properties and patterns

Vector graphics and geometric algebra represent images using mathematical formulas for volumes, surfaces, and curves (including boundaries) that have parameters, coordinates, orientations, colors, opacities, shading, and surface textures. For example, circle information includes radius, center point, line style, line color, fill style, and fill color. Vector graphics includes translation, rotation, reflection, inversion, scaling, stretching, and skewing. Vector graphics uses logical and set operations and so can extrapolate and interpolate, including filling in. Splines with generalized ellipses or ellipsoids represent lines and can represent region boundary lines. Spline sets can represent surfaces using parallel lines or line grids, because they divide surfaces into polygons. Closed surfaces can be polygon sets: for simplicity, polygons can be triangles.

Spatial programming combines vector graphics, geometric algebra, and object-oriented programming. It uses three-dimenional registers. From vectors and bivectors, it makes color atoms, color compounds, and color units, which have spatial and temporal intensive-quantity properties: on frequency, spatial density, and spatial depth/convexity. Color units combine the spatiotemporal properties to have volume texture (microscopic surface texture), an extensive quantity.

From intensive-quantity distance and direction information, spatial programming makes an extensive quantity that puts volume textures at space points.

Volume textures at space points make the visual field. Volume textures model color brightness, temperature, and lightness and so define colors.

8. Machines

Machines can simulate color sensations using a microscopic-surface-texture array with elements with spatial density and depth. Elements are on or off to make brightness.

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