Aspects of human perception

Bastian Rieck

Research group *Computer graphics and Visualization* (CoVis)
Interdisciplinary Center for Scientific Computing

Light & the human eye

Brightness & contrast

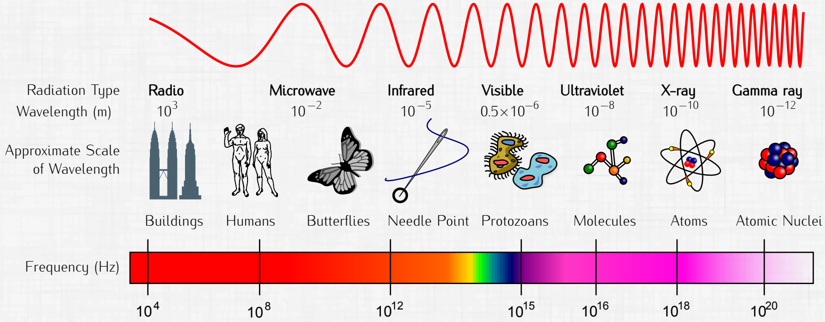
- Optical illusions
- Intensity perception

Colour

Visual attention & practical considerations

Light

- Perception is the ability to see and understand *patterns* in the visible spectrum of the light.
- The visible spectrum comprises wavelengths from approximately 380nm–780nm.
- Some animals are capable of perceiving a larger part of the electromagnetic spectrum, e.g. snakes (infrared) or insects (ultraviolet).

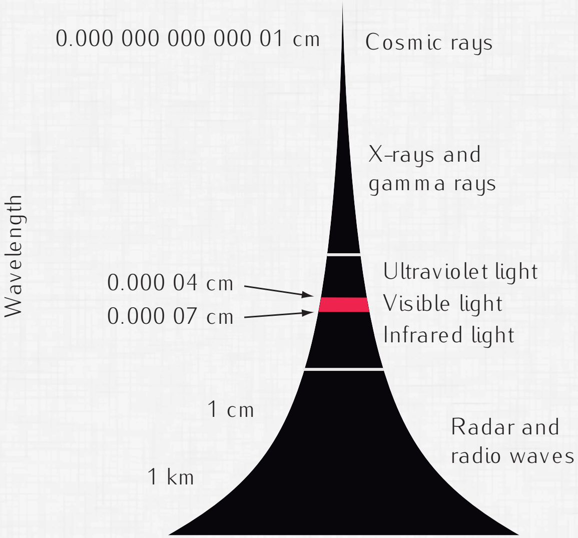


Source: Wikipedia, User *Inductiveload*

The Mantis shrimp

- Up to 16 different photoreceptors.
- Capable of perceiving multi-spectral and polarised light.
- Most complex eyes in the animal kingdom.

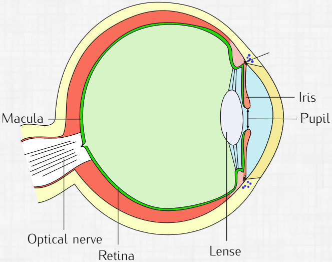
Visible spectrum



Source: [3]

Composition of the human eye

Lense	Focuses a small *inverted* image of reality onto the retina.
Iris	Regulates the amount of incoming light.
Retina	Contains photoreceptor cells (light-sensitive neurons) that perceive optical stimuli (*rods* for low-light perception; *cones* for normal-light perception and colour perception).
Blind spot	No photoreceptor cells because optical nerve is leaving the eye.
Macula	Highest density of photoreceptor cells; high-acuity vision.



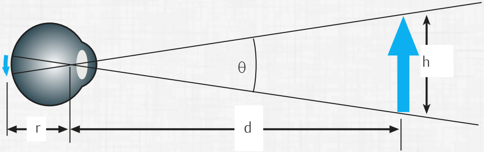
Source: Wikipedia, User *Talos*

Visual angle

Definition (Visual angle)

The *visual angle* (also known as the *angular size* of an object) is the angle under which an object is perceived in the eye.

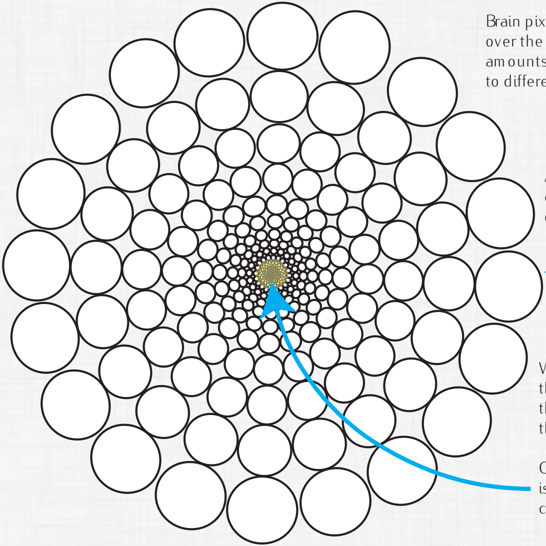
- Your thumbnail at arm's length corresponds to approximately 1°.
- The *fovea centralis* perceives only approximately 2°.
- Formula: $\theta = 2 \arctan\left(\frac{h}{2d}\right)$.



The visual angle of an object is measured from the optical center of the eye.

Source: [3]

Resolution



Brain pixels vary enormously in size over the visual field. This reflects differing amounts of neural processing power devoted to different regions of visual space.

At the edge of the visual field we can only barely see something the size of a fist at arm's length.

We can resolve about 100 points on the head of a pin held at arm's length in the very center of the visual field called the fovea.

Over half of our visual processing power is concentrated in a slightly larger area called the parafovea.

Source: [2]

Visual acuity

"Brain pixels"

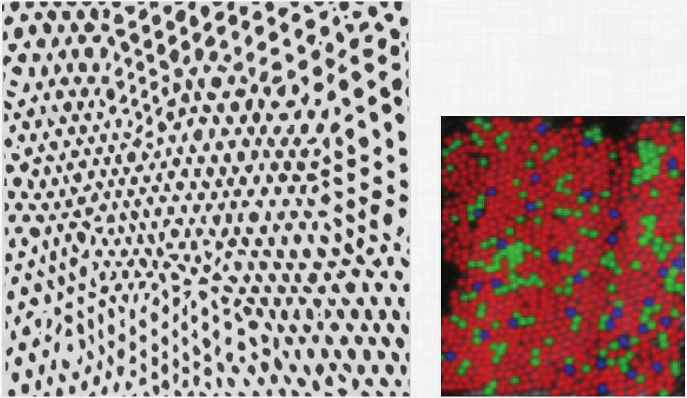
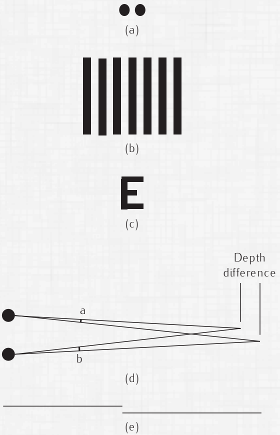


Figure: Photoreceptor cells on the retina.

Source: [2, 3]

Visual acuities

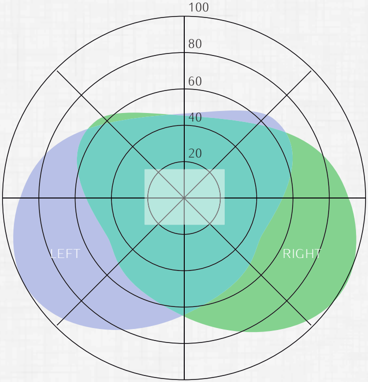
Different resolutions

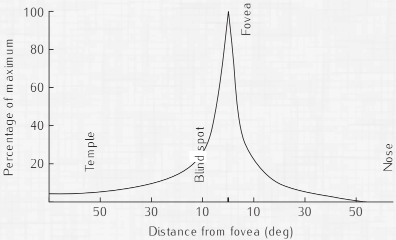


The basic acuities. (a) Point acuity (1 minute of arc): The ability to resolve two distinct point targets. (b) Grating acuity (1 to 2 minutes of arc): The ability to distinguish a pattern of bright and dark bars from a uniform gray patch. (c) Letter acuity (5 minutes of arc): The ability to resolve letters. The Snellen eye chart is a standard way of measuring this ability. 20/20 vision means that a 5-minute letter can be seen 90% of the time. (d) Stereo acuity (10 seconds of arc): The ability to resolve depth. The acuity is measured as the difference between two angles (a and b). (e) Vernier acuity (10 seconds of arc): The ability to see if two line segments are collinear.

Source: [3]

How is acuity distributed in the visual field?

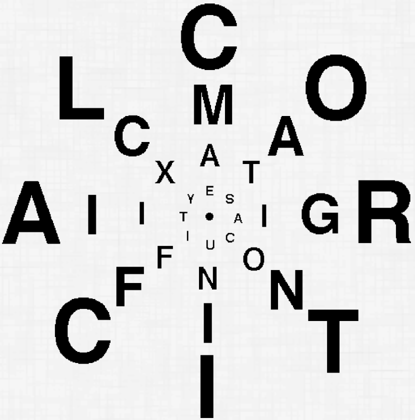




- Centre of visual field: We can resolve 100 points on a pin.
- Boundary of the visual field: We can resolve objects the size of a fist.

Source: [2]

Anstis's eye chart

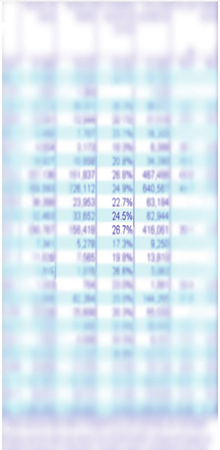


At normal reading length, all the letters should be equally legible.

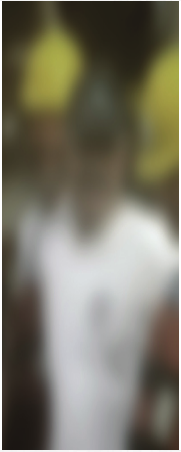
Source: [3]

Visual acuity

Resolution within the visual field



We only process details in the center of the visual field. We pick up information by directing our foveas using rapid eye movements.

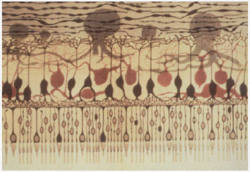


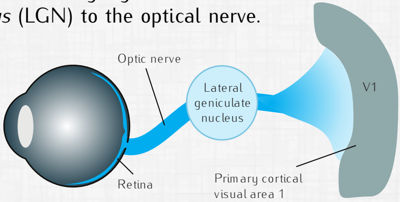
At the edge of the visual field, we can barely see that someone is standing next to us.

Source: [2]

Perceiving brightness

- The retina contains photoreceptor cells and multiple layers of neurons.
- Each neuron communicates with its neighbours using electrical impulses.
- The rate in which impulses are fired may vary, depending on whether a neuron is being *excited* or *inhibited*.
- The layers of neurons converge in *retinal ganglion cells*. These transmit information via the *lateral geniculate nucleus* (LGN) to the optical nerve.





Signals from the retina are transmitted along the optic nerve to the lateral geniculate nucleus. From there, they are distributed to a number of areas, but mostly to visual area 1 of the cortex, located at the back of the head.

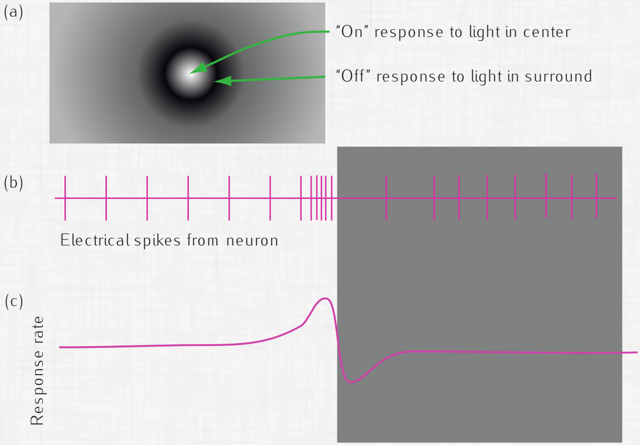
Source: [2, 3]

Receptive field

- The *receptive field* of a cell is the area in which a cell will react to a light stimulius.
- Every pattern of light changes the manner in which the neuron reacts.
- Retinal ganglion cells have a circular receptive field.
- A cell may either be *on-centre* or *off-centre*, depending on whether a stimulus in its centre will cause *excitation* or *inhibition*.

Example

“On-centre” cell



(a) The receptive field structure of an on-center simple lateral geniculate cell. (b) As the cell passes over from a light region to a dark region, the rate of neural firing increases just to the bright side of the edge and decreases on the dark side. (c) A smoothed plot of the cell activity level.

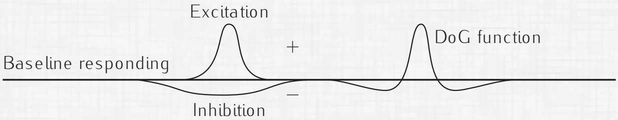
Source: [3]

Model

- "Difference of Gaussians", i.e.

$$f(x) = \alpha_1 \exp^{-\left(\frac{x}{w_1}\right)^2} - \alpha_2 \exp^{-\left(\frac{x}{w_2}\right)^2},$$

  where x is the distance to the centre of the field, w_1 its width, and w_2 the width of the surrounding area.
- The magnitude of the excitation is varied by α_1 and α_2.
- Our eye reacts on *differences* in brightness—it is not capable of measuring absolute brightness values!



Difference of Gaussians (DoG) model of a receptive field.

Source: [3]

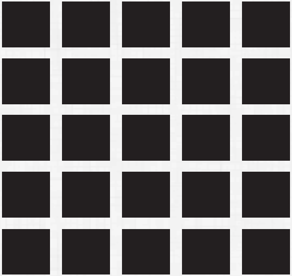
Light & the human eye

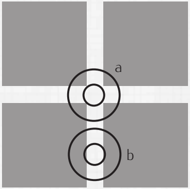
Brightness & contrast
- Optical illusions
- Intensity perception

Colour

Visual attention & practical considerations

Hermann grid

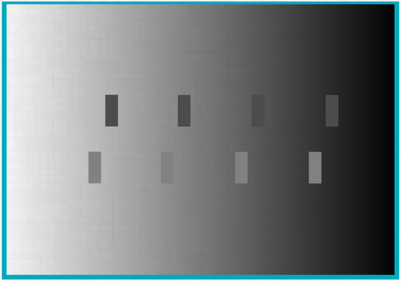


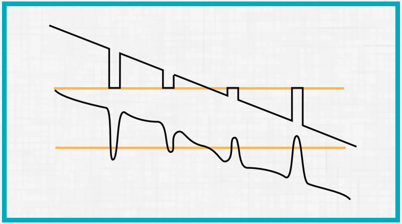


Source: [3]

Simultaneous brightness contrast

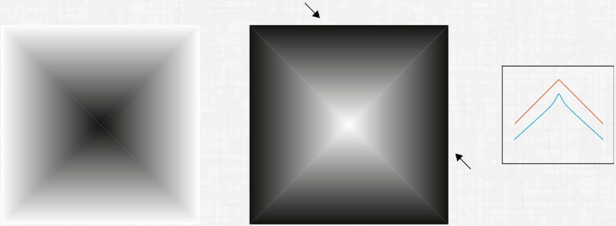
A grey rectangle on a dark background is perceived to be lighter than the *same* grey rectangle on a light background:





Source: [3]

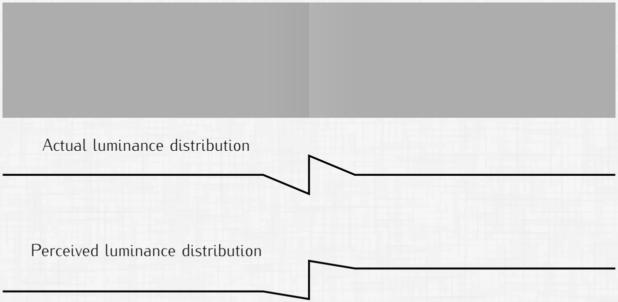
Mach bands



(a) (b) (c)

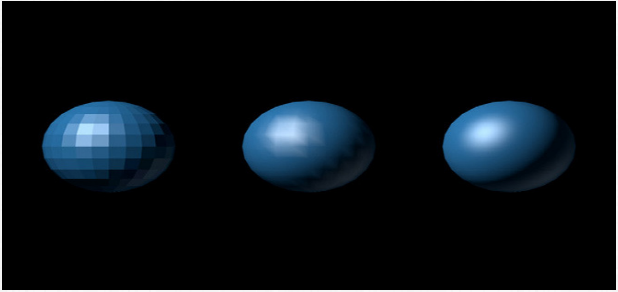
Source: [3]

Cornsweet illusion



Source: [3]

Optical artefacts in *shading*



Source: [3]

Light & the human eye

Brightness & contrast

- Optical illusions
- Intensity perception

Colour

Visual attention & practical considerations

Definitions

Luminance Describes the measured amount of light of a light source.

Brightness Describes the perceived amount of light of a light source.

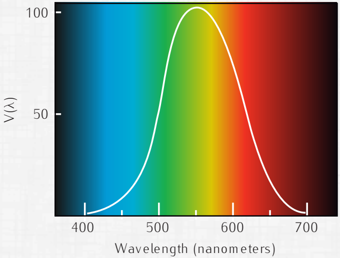
Lightness Describes the perceived reflectance of a surface.

Brightness and lightness are *psychological* variables, while luminance is a physical variable.

Measuring luminance

$$L = \int_{400}^{700} V_\lambda E_\lambda \delta_\lambda$$

Here, E_λ is the light distribution of a light source and V_λ refers to the spectral sensitivity of a "standard human observer" according to CIE. The unit is cd/m^2.



The CIE V(λ) function representing the relative sensitivity of the human eye to light of different wavelengths.

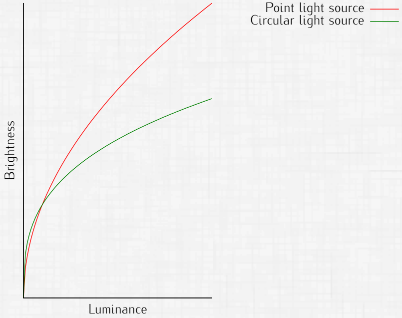
Source: [3]

How is brightness perceived?

Simplified & idealized model

$$\text{Brightness} = \text{Luminance}^n$$

The exponent n depends on the size of the light source. Practical values are $n \approx 0.33$ for a circular light source under a visual angle of 5°and $n \approx 0.5$ for point sources.



Sensitivity in contrast perception

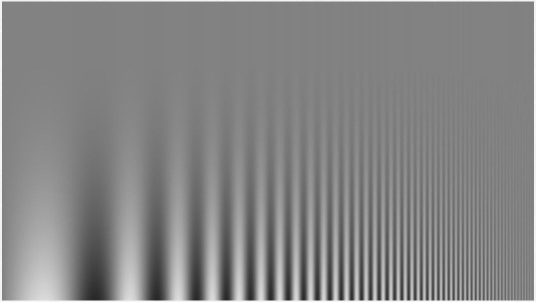
Sine wave grating

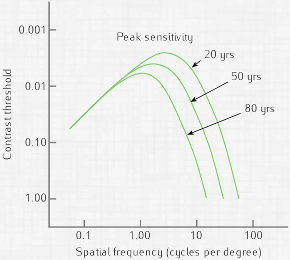
Contrast C describes differences in luminance L:

$$C = \frac{L_{max} - L_{min}}{L_{max} + L_{max}}$$

Perception can be examined using a sine pattern. Multiple parameters are useful here:

- Spatial frequency (number of bands)
- Orientation
- Amplitude
- Phase (lateral offset)
- Size of the covered visual field





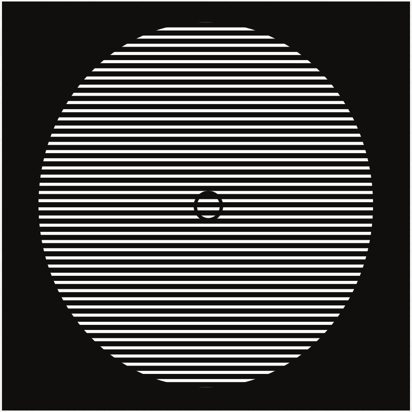
Peak sensitivity
20 yrs
50 yrs
80 yrs
0.001
0.01
0.10
1.00
Contrast threshold
0.1
1.00
10
100
Spatial frequency (cycles per degree)

Source: [3]

Visual stress

Visual stress

- Triggered by different visual stimuli.
- Often a combination of spatial and temporal patterns.
- Wilkins (1995): Striped pattern with a distance of approximately 3/°and flickering with approximately 20kHz.



Source: [2]

Discriminating between shades of grey

- To represent shades of grey, we first need to understand the *perceived* differences between different shades.
- Ideally, equal differences in data should lead to equally-perceived differences in the grey values.
- Weber's law states:

$$\frac{\delta L}{L} = \text{const.}$$

The perceivable difference in grey values is thus independent of the total luminance. Typically, we are able to perceive differences of $\delta L \approx 0.005$, i.e. differences of the order of 0.5%.

Contrast crispening

Shades of grey are perceived as being *more* different if they are similar to the grey value of the background. Most grey-scale colour maps do not factor in this effect.

Source: [3]

Light & the human eye

Brightness & contrast

- Optical illusions
- Intensity perception

Colour

Visual attention & practical considerations

Why is colour perception useful?

At first:

- Reduced relevance in daily life.
- Colour-blind humans typically recognize their deficit in colour perception relatively late in life.
- The spatial arrangement of objects, their shapes, or their direction of movement can be perceived *without* colours.

But:

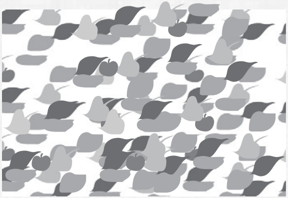
- Colour perception helps perceive camouflage.
- Colour perception helps identify objects faster using their characteristic colour.
- Colour perception helps determine properties of objects ("Is this fruit ripe?", "Is this meat still edible?").

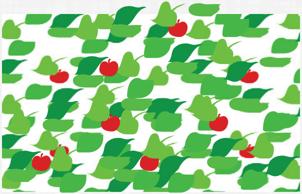
Why is colour perception useful?

Thus:

- Colour is an *attribute* of objects but not a primary feature.
- Useful to mark & categorize objects…
- …but less useful to indicate form, details, or space.

Find the cherries!





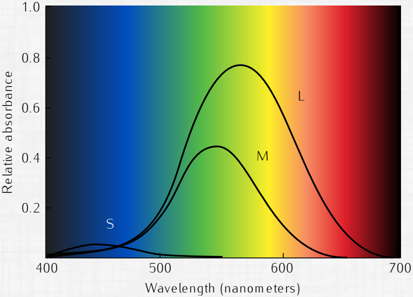
Source: [3]

Definitions for colour perception

- Humans have *trichromate* vision; we have three different types of cone cells (photoreceptor cells) on our retina.
- A *colour space* is an arrangement of colours as a subspace of $\mathbb{R}^3$.
- Three dimensions are sufficient for describing colours because we only have three different types of cone cells.
- Since only three types of receptors are part of colour perception, we can create every colour by mixing three coloured lights.

Why colour spaces? Simpler description and recognition of colours that are perceived as being equal.

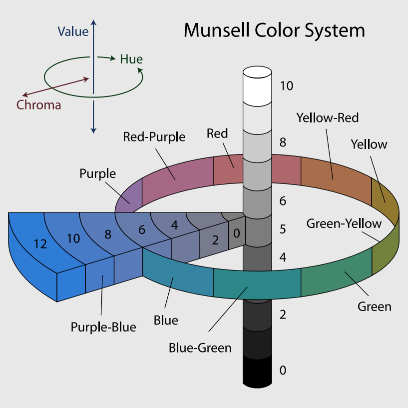
Sensitivity of colour perception



The S-receptor reacts to short wavelengths. It is not overly sensitive in comparison to the other receptors. This is one of the reasons why blue text on a black background can be hard to read.

Source: [3]

Munsell system



Based on psychological aspects: Value (lightness), hue ("tone"), and chroma (colour purity). The difference between neighbouring colours is approximately equal. Complementary colours are placed opposite to each other. Additive mixing results in a neutral grey colour with the same value.

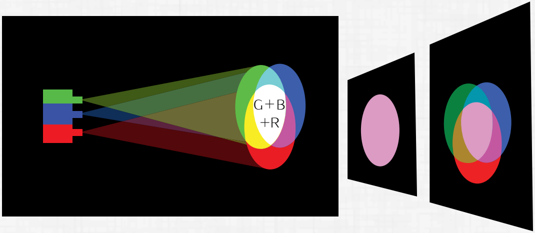
Source: Wikipedia, Jacob Rus

Measuring colour

We can create every colour by *additively mixing* the three primary colours (either as a light source or a physical colour):

$$C \equiv rR + gG + bB$$

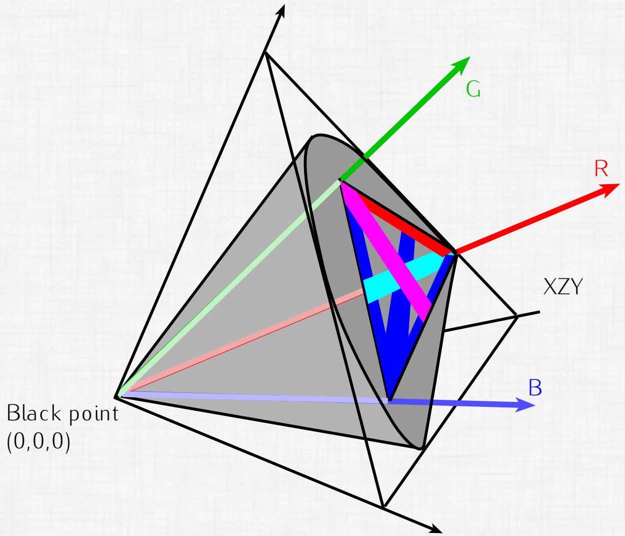
Here, R, G, B denote the corresponding light sources and r, g, b the amount of light.



Source: [3]

The CIE system

- Commission Internationele de l'Éclairage.
- Measuring colours using “standardized observer” (“typical” human perception).
- Based on tristimulus theory (X, Y, Z).
- Y equals *luminance*.
- Created using mathematical criteria, not physical properties of light.



Perceivable colours are contained within the grey volume. The pyramidal volume shows the *gamut* of a typical computer monitor. Source: [3]

Coordinate transformations

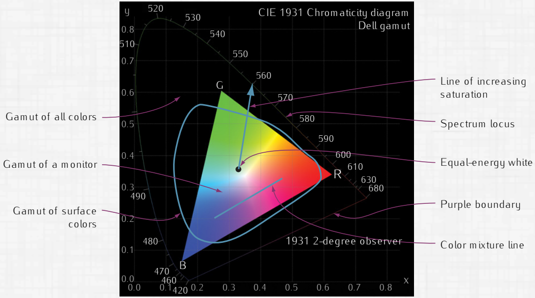
- Colours in the coordinate system of tristimulus theory are rather abstract.
- Usually, we convert them to *chromaticity values*:

$$x = \frac{X}{X+Y+Z}$$
$$y = \frac{Y}{X+Y+Z}$$
$$z = \frac{Z}{X+Y+Z}$$

Since $x + y + z = 1$, it suffices to give x- and y-coordinates. This leads to the CIE chromaticity diagram.

CIE chromaticity diagram

- If two coloured light sources are represented as points in the diagram, all their mixtures lie on the line connecting them.
- Three coloured light sources define a triangle in the diagram. It contains all colours that may be created using these sources.
- The spectral locus contains all colours that consist of a single wavelength only.
- The line of purples connects both ends of the spectral locus.
- The white point has coordinates $x = 0.333$, $y = 0.333$. On the line from this point to arbitrary colours, the perceived colour does not change.
- Complementary colours are found by extending a line through the white point.

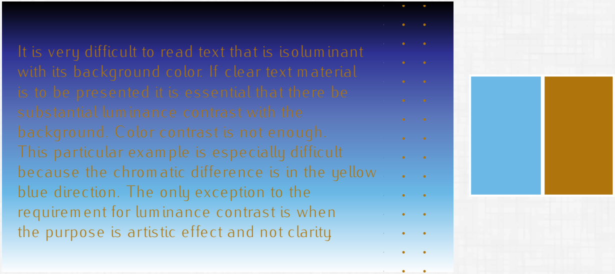


Source: [3]

What is a good colour space?

- Colour spaces in which the spatial distance of two colours corresponds to their perceived distance are very useful. For example: Colours for map representation, models, etc.
- Imprtant: CIE XYZ space does not satisfy this criterion.
- But both *CIElab* and *CIEluv* do and conversion is easily possible.
- Here: Euclidean distance between colour vectors corresponds to perceivable difference.
- Application: Simple *clustering* on colour images!

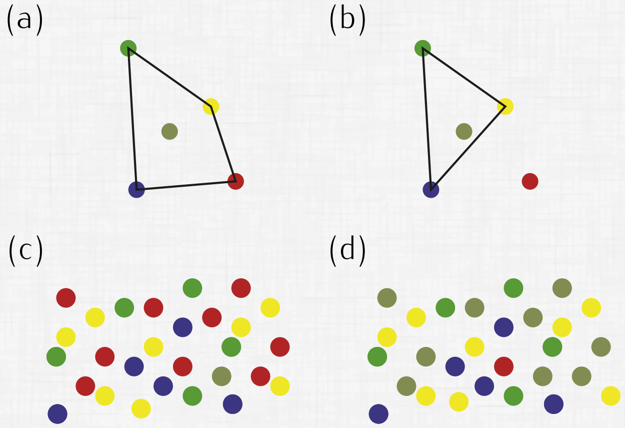
Iso-luminance



Iso-luminance refers to the fact that two colours vary only in their chromatic values but not in their luminance. This makes the perception of details almost impossible. Here, grey values are more useful for transporting information.

Source: [2]

Application: Choosing object colours



To ensure that the colours are perceived as different, the colour of a new object should be chosen from outside the convex hull of the other colours.

Source: [2]

Application: Choosing object colours

Things to remember

Distinctness Colours should be distinguishable from each other.

Unique hues Complementary colours (blue–yellow, red–green, black–white) are perceived well in almost all cultures.

Background contrast Keep in mind that colours are perceived differently depending on the background. Avoid iso-luminance!

Colour-weakness Avoid red–green colour coding.

Number of colours Only about 5–10 colours may be distinguished rapidly.

Size The size of coloured objects needs to be sufficiently large. In general, the smaller an object is, the more saturated and stronger its colour needs to be.

Light & the human eye

Brightness & contrast

- Optical illusions
- Intensity perception

Colour

Visual attention & practical considerations

How often does the number “3” appear here?

45929078059772098775972655665110049836645
27107462144654207079014738109743897010971
43907097349266847858715819048630901889074
25747072354745666142018774072849875310665

How often does the number “3” appear here?

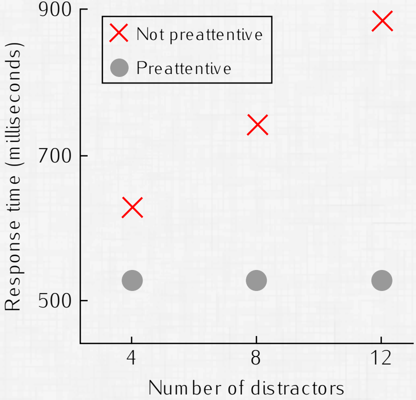
45929078059772098775972655665110049836645
27107462144654207079014738109743897010971
43907097349266847858715819048630901889074
25747072354745666142018774072849875310665

Pre-attentive processing

- Some visual information are readily apparent. They “catch our eyes” immediately.
- We recognize and process them *before* we view them consciously.
- This sort of processing or cognition is hence referred to as *pre-attentive*.
- Since the information is processed very rapidly, pre-attentive processing can be a powerful tool for visualizations.

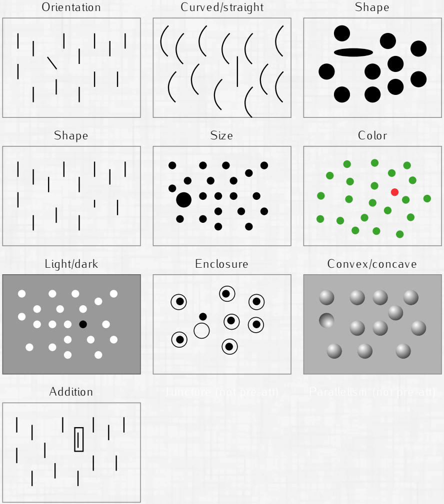
How to measure pre-attentive processing

- Experimental setup: Check whether a test subject is capable to see a target object among a set of *distractors*.
- If the time required for perceiving the target object is *independent* from the number of distractors, the object is perceived pre-attentively.



Source: [2]

Examples



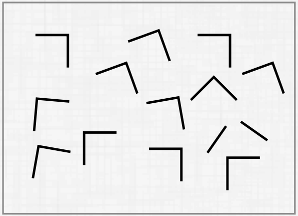
The strength of these stimuli is different.

Colour, orientation, size, and contrast are among the strongest stimuli.

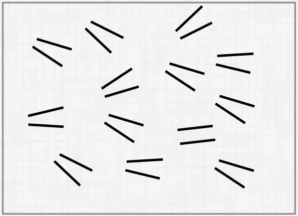
Source: [3]

Not all stimuli are pre-attentive...

Juncture (not pre-att.)



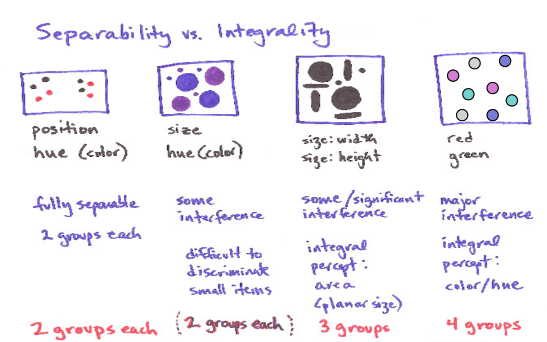
Parallelism (not pre-att.)



Source: [3]

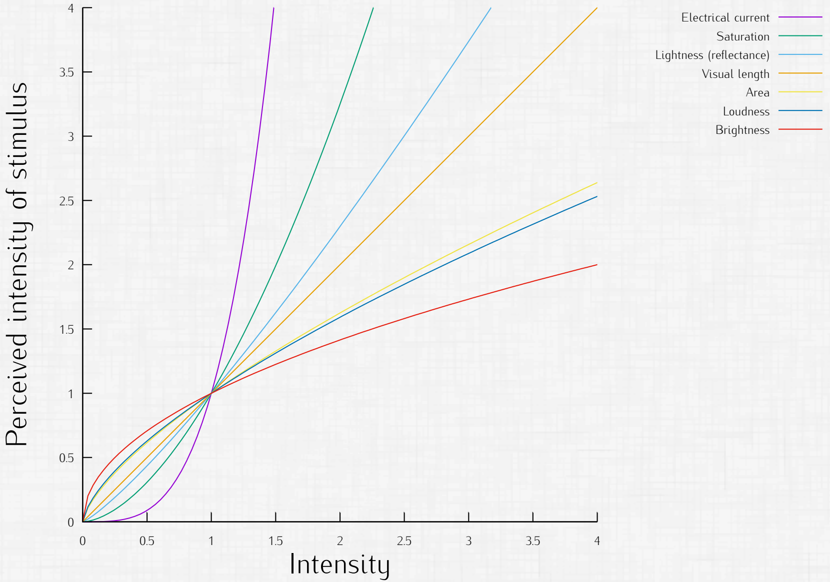
Rules

- If too many pre-attentive stimuli are present, individual stimuli will not be recognized as rapidly.
- The combination of multiple pre-attentive stimuli is not processed pre-attentively in general.



Source: T. Munzner, VizBi 2011

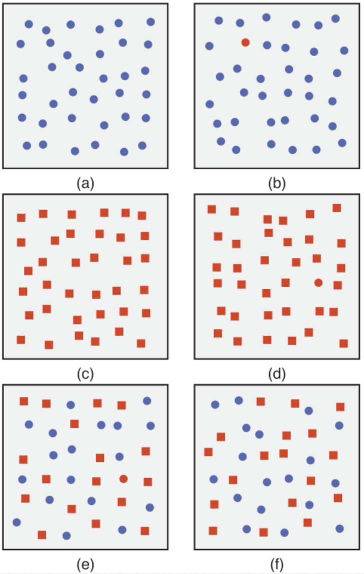
Stevens' power law



Exponents: 3.5, 1.7, 1.2, 1.0, 0.7, 0.67, 0.5

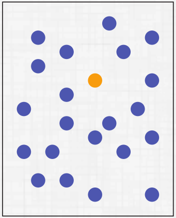
Examples

Delayed search rate for combined stimuli

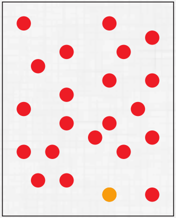


Source: C. Healey, Perception in Visualization

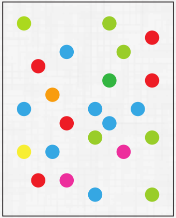
Varying search rates



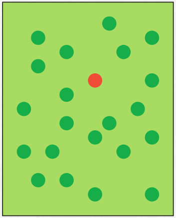
The larger the chromatic difference between the target symbol and the other symbols, the easier the search.



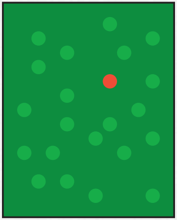
When there is only a small color difference from non-target symbols, the search is difficult.



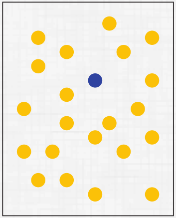
When there are many non-target symbol colors, the search is the most difficult.



If non-target symbols are similar to the background, they are easy to exclude from the visual search.



A luminance difference plus a chromatic difference from other symbols and the background leads to the easiest search.

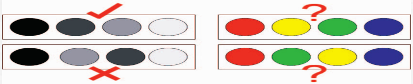


A dark target on a light background with light non-target symbols can be as effective as the reverse.

Source: [2]

Choosing a colour map

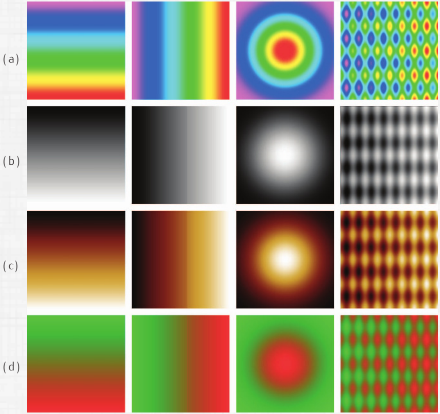
- Humans are able to sort colours by *luminance*...
- ...but not by hue.



The rainbow colour map is completely unsuitable for serious visualizations. It introduces visual artefacts such as perceived boundaries that are not present in the data.

Source: [1]

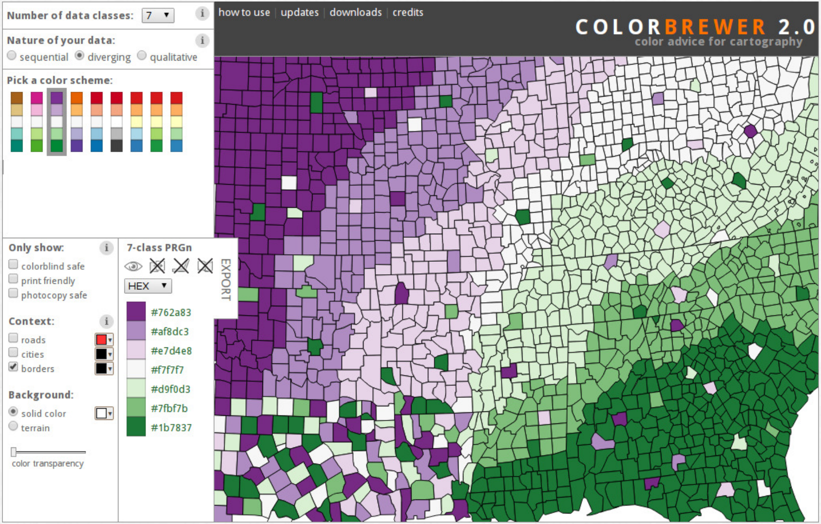
Comparing some colour maps



Four data sets visualized with (a) rainbow, (b) gray-scale, (c) black-body radiation, and (d) isoluminant green–red color maps. Apparent sharp gradients in the data in (a) are revealed as rainbow color map artifacts, not data features, by comparing this row with the same data viewed using the other color maps. Conversely, the sharp gradient found at the center of the second data set (see the second column) shown in the gray-scale and black-body radiation (and to a lesser extent, the isoluminate green–red) images is not found in the corresponding image with the rainbow color map.

Source: [1]

Where to find good colour maps?



Literature

[1] David Borland and Russell M. Taylor II.
Rainbow color map (still) considered harmful.
IEEE Computer Graphics and Applications, 27(2):14–17, March 2007.

[2] Colin Ware.
Visual thinking for design.
Morgan Kaufmann, 2008.

[3] Colin Ware.
Information visualization: Perception for design.
Morgan Kaufmann, 3rd edition, 2012.