Perceptual Aspects in Visualization

2018-10-01

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Overview

The world is not like we see it (objectively speaking)

Humans are not reliable in making visual assessment

Perceptual & cognitive limits
Overview

Quick overview over this lesson

• Physiology of the human eye
• Visual acuity and performance
• Color, brightness and contrast
• Use of colors
• Pop-out effect
• Cognitive limits
Definition:

Visual angle is the angle $\alpha$ subtended by an object of size $s$ at some distance $d$ to the observer.

When describing visual acuities and properties, visual angle is used because it is independent of viewing distances and objects viewed.

\[ s = 2 \cdot d \cdot \tan\left(\frac{\alpha}{2}\right); \alpha = 2 \cdot \tan^{-1}\left(\frac{s}{2d}\right) \]
Retina

Receptors of two types: cones and rods

**Rods** (sv. stavar):
- Sensitive at low light level
- Approximately 100 million
- Contribute little at daylight (oversaturated at daylight levels)
- Are interconnected over larger areas

**Cones** (sv. tappar):
- Effective at daylight levels
- Color sensitive
- Are highly packet at the fovea (180 per degree visual angle)
- Approx. 100,000 at the fovea
- Approximately 6 million in total
Retina

*Blind spot*
At approx. 15 degrees lateral

Experiment: Two thumbs at arm length

*Fovea*
Highest receptor density

1,5-2 degrees visual angle

Corresponds to an area of size $s=2.5$ cm at $d=70$ cm viewing distance
Fovea Visual Angle

Focal field of view defined 1-2 degrees visual angle

Size of a thumbnail at approximately arms length

\[ s = 2 \cdot d \cdot \tan \left( \frac{\alpha}{2} \right); \alpha = 2 \cdot \tan^{-1} \left( \frac{s}{2d} \right) \]
Retinal Receptor Mosaic

- No “regular grid”

- Uneven distribution of S M and L cones (less blue sensitive receptors in fovea)

- Sensor “density” is 20 arc sec.

- “cone footprint” ~ 0.068 mm at 70 cm viewing distance

Image adapted from http://rit-mcsl.org/fairchild/WhyIsColor/images/ConeMosaics.jpg
Visual Acuities

Point acuity: 1 minute of arc
Grating acuity: 1-2 minutes of arc
Letter acuity: 5 minutes of arc (5.8 mm at 4 meters distance)
Vernier acuity: 10 seconds of arc

Acuity fall-off across visual field: See figure right
Acuity depends on brightness/contrast
Several receptors interconnected -> superacuities

Cones and rods are interconnected in larger regions and respond to visual stimuli
Visual Acuities

Utilization of Vernier acuity: Reading caliper scales
Visual Acuities – Some illusions

Experiment: Visual illusion due to limited retinal resolution

First: Look at this image in full-screen (17” monitor at 70cm viewing distance)
Second: Step back about 4 meters from the screen.
What do you observe? can you explain?
Visual Acuities – Some illusions

The low-frequency component of the image. At far viewing distances they become prominent because the high frequency spatial components in the image cannot be resolved by the HVS.
Spectral sensitivity of cones

Spectral range of visible light 380nm – 680nm

Spectral sensitivity function

Three peaks: 430 nm, 540nm, 580nm
Relative spectral sensitivity of the eye

Green 555 nm, peak
Blue 450 nm, 4% of max sensitivity

=> Blue is not a preferred choice in presence of green and/or red
Lens

Chromatic aberration

Lens power varies for color

Blue appears “out of focus”

Receptor sensitivity for blue is only 5% of maximum sensitivity for green

(recall prev. slide)

Optical power of lens depends on among others:
- lens shape
- index of refraction
- wavelength of the light

Dispersion caused by varying refractive index for different wavelengths
The “blurry” blue
Chromostereosis
Some people see the blue
Closer than the red
But other people see
The opposite effect
Properties of the visual field of view

Periphery (horizontally up to 200 deg.)
Central FoV (vertically approx. 120 deg.)
Receptor distribution and properties
Stereo-overlap (approx. 120 deg.)

Most prominent figures at 4-5 deg. visual angle
Approximately 6 cm at 70 cm viewing distance

Rapid changes are detected in peripheral field of view
Properties of the visual field of view

Most prominent figures at 4-5 degrees visual angle

Approximately 6 cm at 70 cm viewing distance
Luminance, lightness and brightness

Definitions:

**Luminance** is the measurable amount of light coming from some region in space. It is a physical property that can be exactly measured (e.g. Candela per square meter).

**Brightness** is the perceived amount of light coming from self-luminous objects.

**Lightness** refers to the perceived reflectance of a surface. A white surface is light a black one is dark.
Color value assessment

Estimation of the lightness levels of colors depends on surround
Color value assessment

Color not useful as a means to encode/read absolute value
Perception of lightness/brightness levels

The human visual system is not an absolute measuring device.

Perceived lightness/brightness depends on a number of factors:

• Overall ambient light level adjustment (photo pigment bleaching)
• The illuminant and spatial illumination conditions (see illusion next slide)
• Colors in the surround of an object (see illusion picture)
• Local contrast effects

Example:

A black object on a sunny day outside reflects more light than a white object inside an office room. Yet, we perceive the black object as dark and the white one as light.
Interpretation of color

Again, the human visual system is not an absolute measuring device.

Also, perceived color depends on a number of factors:

- Overall ambient light level adjustment (photo pigment depletion) (causing “negative” after images)
- Colors in the surround of an object (see illusion picture)
- Local contrast effects
Interpretation of color

Receptor bleaching (photochemical bleaching)
(-→ visual phototransduction, photopsin, protein-pigment complex)

Negative afterimages due to photo-pigment depletion

(Helmholtz 1866, Hering 1872)

Example: See next slide

Other explanation in the absence of light: Neurons fire in opposite state after termination of a prolonged stimulus (overshoot).
Color Adaptation

What color is the shirt of the lady not raising her hands?
Color Adaptation

Here is the original image, without filter.

And quite right. The color is yellow!
Color Adaptation

Now let's copy the top from picture 1 into the original picture 2?

Well, the color of the top in picture 1 was in fact green!
Color Adaptation

Here is the direct comparison
Contrast

Visual perception is not directly based on the neural signals of the receptors in the retina, instead there is some neural processing in several layers of retinal ganglion cells.

Fig. 15. Diagram of the organization of center-surround circuits using both horizontal cells and amacrine cells.
Ganglion cells are organized with circular receptive fields that can have an on-center or off center. Size of receptive fields vary from central field of view to periphery.

Lateral inhibition (Hartline 1940)
Contrast

Difference of Gaussian model  (compare figure 3.3)
Simultaneous contrast

The DOG processing model facilitates enhanced perception of contrast -> *simultaneous contrast*

Color Ramp example

See more examples on next slides
High Contrast and Visual Stress

Spatial frequency of 3 cycles per degree visual angle

In addition: Strong contrast (luminance)

See next 2 pictures
Opponent Process Theory

Ewald Hering (1920)

- Six base colors (unlike trichromacy theory)
- Differential and additive processing of receptors signals
- Naming-, cultural and neurophysiological support for this theory

Cone signals are hierarchically combined and processed in three channels:

- Yellow-Blue (R+G-B)
- Red-Green (R-G)
- Black-White (R+G+B)
Ethnographic studies

Most frequent colors

Number of colors we can distinguish vs. number of different colors we can tell?

Colors that are not basic are difficult to remember (orange, lime green ...)

Criteria for use of color as label
Distinctness, uniqueness, contrast with background, color blindness, number, field size, conventions
Color as label
Conventions and learned knowledge

Name the colors of the words!

Yellow
Green
Blue
Orange
Gray
Red
Green
Color as label
Conventions and learned knowledge

Name the colors of the words!

Yellow
Green
Blue
Orange
Gray
Red
Green
Colors can show detail

Example: Reading complex documents on a handheld mobile device
   (-> see letter acuity)

Remember: Visual acuities depend on lightness contrast
   -> most important for readability of text and fine structural detail

Therefore: Visual acuity depends on large $\Delta L$ of (color) stimuli

Perceptual dimensions of color:
   \textbf{Hue} (chromaticity, spectral wavelength)
   \textbf{Saturation} (purity, degree of white)
   \textbf{Lightness} (value, level)
Colors can show detail

Colors differ in hue

\[ \text{Text}_{\text{HSL}} = (200,128,128) \]

\[ \text{Background}_{\text{HSL}} = (72,128,128) \]

Colors differ in saturation

\[ \text{Text}_{\text{HSL}} = (200,128,128) \]

\[ \text{Background}_{\text{HSL}} = (200,0,128) \]

Colors differ in luminance

\[ \text{Text}_{\text{HSL}} = (200,128,128) \]

\[ \text{Background}_{\text{HSL}} = (200,0,128) \]
Colors can show detail

Take-away-message: Appropriate choice of colors is important depending on the intended use/effects.

If contrast is the objective, use color pairs with large $\Delta L$

Examples:
Spatial details (e.g. text)
Contours and shape in color maps

Minimize $\Delta L$ for color pairs if lo-contrast is the objective

Example:
Reduce risk for visual stress
Avoid undesired artifacts (mach-banding)
De-emphasize regions with less relevance (lower attention)
Colors call attention

Preattentive processing of visual information is performed automatically on the entire visual field detecting basic features of objects in the display. Such basic features include colors, closure, line ends, contrast, tilt, curvature and size. These simple features are extracted from the visual display in the preattentive system and later joined in the focused attention system into coherent objects. Preattentive processing is done quickly, effortlessly and in parallel without any attention being focused on the display. [Treisman, 1985, Treisman, 1986]

Typically, tasks that can be performed on large multi-element displays in less than 200 to 250 milliseconds (msec) are considered preattentive. [Healey, 2005]

- Saturated colors on an achromatic (desaturated) background/context are processed preattentively.
- Identification of colored features in this context requires no focused attention / cognitive processing.
- Pre-attentively processed features are useful for rapid search tasks!
Visual Pop-out

Definition of visual pop-out

Visual pop-out occurs when visual features are processed pre-attentively. I.e. in a visual task involving identification of visual targets, the time needed for identification is not depending on the number of the non-target elements (distractors).

Chroma differences are useful for visual pop-out.

Ready for a test?
A set of characters (letters and numbers). Exactly how many numbers do you count!
Visual Pop-out

Example $^{23+?}$
Visual Pop-out

Example _45+?
Visual Pop-out

Example \(45+4\)
Colors represent quantities

Color maps -> representation of relatively ordered data/values

Perceptual linearity
Constant lightness contrast
Color maps for deviation detection

Not suited for absolute quantitative assessment!

Experiment: Sorting color-sequences
Use of color – Color sequences

Correct solution 1: Heated Iron

Experiment

<table>
<thead>
<tr>
<th>L</th>
<th>Q</th>
<th>F</th>
<th>K</th>
<th>Z</th>
<th>P</th>
<th>1</th>
<th>R</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>81</td>
<td>102</td>
<td>117</td>
<td>156</td>
<td>153</td>
<td>143</td>
<td>155</td>
<td>203</td>
</tr>
</tbody>
</table>
Use of color – Color sequences

Correct solution 2: Gray scale

Experiment
Correct solution 3: Random H, >L

Experiment
Use of color – Color sequences

Correct solution 4: Spectral, constant S+L

Experiment
Example from a real case in the process industry

Efficient use of color
Pre-studies

Color mapping designs for JND tasks

Graphical mappings

2D map

3D map

3D cylindrical

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Validation study in the field
Some results

Detection Times (Median) Between Teams

Detection Time [s]

2D Map 3D Field 3D Tube

B-Team F-Team

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Visualization
Potential and pitfalls

Visualization has an enormous potential!

“An image tells more than thousand words”

But:

“The eye sees what it wants to see”

CAVEAT: Illusions and perceptual limits
Visualization

Ambiguous representations

"The eye sees what it wants to see?"

Sax player or woman's face?
Seal or donkey's face?
Bacchus or couple kissing?

How you interpret the visual percept depends among others things upon your personal attitude, expectations (context).

But visual angle is important, too!
Visual elements that subtend 4 degrees visual are most prominent.
Visualizations have enormous potential!

"An image tells more than thousand words"

But:

"Human’s capacity for attention is limited"

Example: “Inattentential blindness” aka “perceptual blindness”
Inattentional blindness

Task: Count the passes of the black team in the following video!
Visualizations have enormous potential!

"An image tells more than thousand words"

But:

"Human short term memory (working memory) is limited"

Example: “Change blindness”
Change Blindness:
Change Blindness:
Visualization

Change Blindness:

Fairly large changes in a scene are not detected if they coincide with some visual disruption. (e.g. saccades, blinks, transient noise and distraction)

Failure to compare relevant visual information from current scene with visual short term memory.
Visualization
Potential and pitfalls

The visual percept of size is not constant.

Retinal size of objects is does not predict real size.

Example:
Mix of 2D spatial size and 3D perspective cues
The visual percept of size is not constant.

Retinal size of objects does not predict true size.

Example:
Mix of 2D spatial size and 3D perspective cues

Beware of this when making judgements of length/sizes in mixed visualizations (2D/3D) e.g. using 2D bars in 3D landscape
Visualization
Potential and pitfalls

Illusions from deliberately chosen inconsistent 3D cues (Ames Room)

By Adelbert Ames Jr. (Ophthalmologist), 1934;