Summary of Colin Ware's "Information Visualization: Perception for Design"

Hugo Rivera, Spring 2015

Notes taken for Visualization CSE 476 taught at the New Mexico Institute of Mining and Technology, Spring 2015.
Summarize chapters 1 to 11 and Appendix D.

Contents

I Chapter 1: Foundations for an applied science of data visualization

Visualization is the application of vision research to problems of data analysis. As visualization becomes more important, so does its scientific understanding. Sensory and arbitrary symbols are split by fundamental differences, but classification can be difficult. Consistent notation is most important. This book assumes all humans have more or less the same visual system.

I.1 Visualization

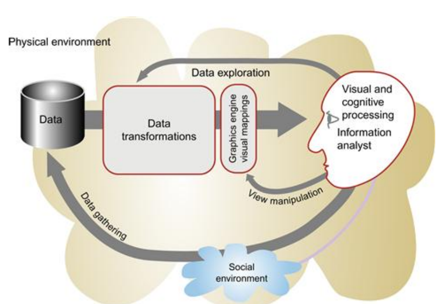

Figure 1: Stages of visualization

Visualization A graphical representation of data or concepts. Old: constructing a visual image in the mind.

Benefits of visualization :

1. Comprehend huge amounts of data
2. Perception of unanticipated, emergent properties
3. Problems with data become apparent
4. Understanding of both large-scale and small-scale features
5. Hypothesis formation is encouraged

Visualization stages form feedback loops in the search for new information:

Data gathering is the longest feedback loop.

Visualization can be highly interactive

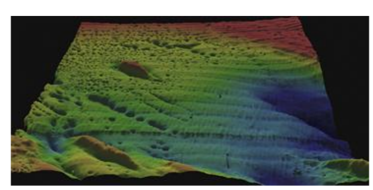

Figure 2: Pasamoquoddy bay scans. A lot of data. Roll of the ship was not corrected for.

I.2 Semiotics

Semiotics the study of making meaning. Signs, analogy, indication, designation, metaphor, symbol, communication.

Counter-argument: diagrams are arbitary, all symbols are learned thus one visualization is as good as another regardless of ease of perception.

This debate helps us decide where visualization science is useful and where we should consult a trained designer.

Semiotics of graphics dominated by non-rigorous philosophers. What is a visual language?

Biggest threat philosophers argue that truth is only so in the context of its creators' culture. Meaning is curated by culture. All representations have meaning to those trained/raised to know them.

These arguments are rejected we can have a new semiotics based on scientific evidence, not philosopher's claims.

People can interpret pictures without training clearly (2 studies). The outline of an object and the object itself excite similar neural processes.

I.3 Sensory vs Arbitrary

Sensory is defined here as the aspects of representation that are expressive due to the natural perceptual processing power of the brain. Full scientific methodology can be applied. Nearly universal.

Arbitrary is defined here as the aspects of representation that must be learned. Interpretive methodology needed.

Example circles in nearly all cultures represent a bounded region

We reject the idea that the visual system can adapt to any universe, and that our vision is intertwined with this planet.

Many specialized regions in our brain develop only for their single purpose, not a tabula rasa.

Small adaptations cats raised in a world of only vertical stripes develop an unusual number of vertical-edge detectors

Macaque Monkey's visual system: V1 (orientation, color, stereo depth) $\rightarrow$ V2 $\rightarrow$ V3 $\rightarrow$ V4 (Color, motion, elements of form) and other systems. Also: object perception, color constancy, attention, visual working memory.

Sensory representations work because they are well matched to the first stages of perception.

1. Understanding without training
2. Resistance to alternate denotation
3. Sensory immediacy
4. Cross cultural validity

Vision researchers and biologists can test claims about sensory representation.

Arbitrary codes are socially constructured

1. Hard to learn
2. Easy to forget
3. Embedded in culture and applications
4. Formally powerful, can be matched to rigorous languages

Sensory and arbitary are intertwined but the visualization designer must still be able to apply the science of visualization

Figure 3: Left visualization is easier to interpret

I.4 Gibson's Affordance theory

Affordances are possibilities for action that can be percevied

Directly seen, not inferred from sensory cues.

Action-based perception!

We do not perceive points of light and go up from there, our visual system works from top to bottom.

Three problems :

1. Computer graphics are very indirect, detached from the way we interact with them
2. No clear physical affordances in any graphical user interface. Buttons are arbitrary
3. Gibson rejected visual mechanisms. Mistake. Color perception is an inborn trait, it is actually a thoroughly studied system, and it is entirely bottom-up.

I.5 A model of perceptual processing

Stage 1: Parallel processing, low-level properties primitive, specialized and fast. Bottom-up, visual salience. If information must be understood quickly, here is where optimizations are needed.

Stage 2: Pattern Perception Rapid processes divide the field into regions and simple patterns like contours and regions of shared color/texture. Motion. Flexible. Deals with the massive amount of data from stage 1 and tunes queries using the higher-level process of attention. Slower, serial. One to three objects can be held for a second or two.

Stage 3: Visual working meory highest level. Sequence of visual queries. Only a few objects held at a time. Constructed from the lower levels.

Attention The top-down signal that consolidates and enhances the jobs of the visual system. Multifaceted, pervasive.

I.6 Costs and Benefits of Visualization

Must measure value in some way to optimize a system. Workers will work easier, less stress. A scientific discovery could be made.

Cost for user: time to learn

Benefit for user: improved cognitive workload

Cost for dev: time to develop visualization, cost to market, manufacture, service

Benefits for dev: units sold, revenue

I.7 Types of data

1. entities, relationships, attributes
2. dimensionality: 1,2,3 and up
3. types of numbers
4. uncertainty
5. operations such as arithmetic, merging, removing
6. metadata: data about data, who/what, transforms and uncertainty

II Chapter 2: Environment, Optics, Resolution, Display

The computer screen is utterly simple when compared to the richness of the visual world. Remarkably powerful. Can reproduce many important aspects of vision. Typical Monitor typically occupies 5% to 10% of our FOV, but in the fovea, which holds 50% of our power. Lack of focal depth of focus is the biggest omission. Fortunately, the most important perceptual patterns are 2D.

II.1 The Environment

The Environment we should be able to transfer skills obtained in interpreting the real environment to understanding our data

Visible light Range from 400 to 700 nanometers.

Ecological optics J.J. Gibson's discipline. Surfaces, fibers, edge/corners are tangible, unlike the abstract geometrical planes and lines.

Ambient optical array the spherical array of light from all directions to a region in the environment. 3D mess of photons is simplified to a 2D array. Expressible through pixels

Optical flow perception of motion is as important as that of static patterns, albeit less well understood

Textured surfaces and gradients fundamental property. It is not "chart junk," especially in 3D graphics.

Paint model of surfaces although textures are complex in nature, they can be mostly modeled using the four following shading methods.

Lambertian shading computationally simple, surface color remains constant at all angles. A perfectly matte surface. Brightness depends only on cosine between light and surface normal.

Specular shading light reflected directly off surface. Highlights on glossy objects. Mirror reflection.

Ambient shading ambient light comes from everywhere except the source of light. Truly complex (see radiosity technique) to calc, but simplified in computers as a constant.

Cast shadows on itself or other objects. Give height.

Simpler lighting models may, arguably, be closer to the model our own brain uses; thus easier to perceive.

Ambient occlusion different amounts of light reach different points depending on their exposure to the source. Great for depth in complex models.

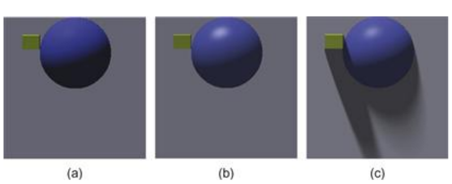

Figure 4: Three types of shading

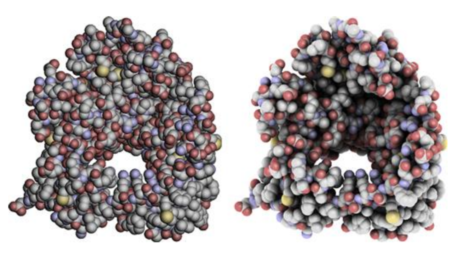

Figure 5: Occlusion in a molecule visualization

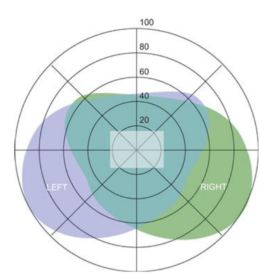

Figure 6: Visual field. Center square is a typical monitor

II.2 The Eye

We do not see what is on the retina. The locus of conscious perception is higher up, with details lost.

Visual angle angle subtended by an object at the eye of an observer. When 57cm away, 1cm is about 1 degree. Good apprx. for computer monitors.

Lens 59 diopters. Becomes less flexible with age. Lose about 2 diopters per decade.

Depth of Focus At 50cm 43cm are near and 60cm are far. At 3m, 1.5m is near and ∞m is "far".

Augmented reality Superimpose visual imagery on the real world. Perspective is easy, eye position is difficult as is the design of optic systems to make light, undistorted and portable systems.

Virtual reality optical blur and optical distance must be simulated to accurately show depth. Eye tracker to determine the user's focus.

Chromatic aberation our eye is uncorrected for this. Blue on black is nearly indistinguishable. Can cause strong depth effects! Red on black seems nearer than blue on black for most people, though effect can be reversed.

Retina has two photoreceptor cells: rods (100 million) for low-light conditions, they are usually too stimulated to provide help and cones which are sensitive under normal levels (6 million).

Fovea center of the retina, densely packed only with cones. 2-degree field, best in the central $\frac{1}{2}$ degree.

Simple acuities :

- **Point (a)** acuity (1 minute of arc)
- **Grating (b)** acuity, bars (1 to 2 minutes of arc)
- **Letter (c)** acuity (5 minutes of arc). 20/20 vision means a 5 minute letter can be resolved 90% of the time.
- **Stereo (d)** acuity, for depth (10 seconds of arc)
- **Vernier (e)** acuity, ability to see if two line segments are colinear (10 seconds of arc)

Binocular abilities to perceive acuities improves by 7% and contrast sensitivity increased by $\sqrt{2}$.

Acuity distribution Only $\frac{1}{10}$ of detail 10 degrees from the fovea. Inverse square law.

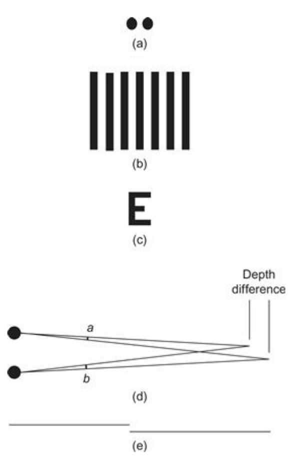

Figure 7: Simple acuities

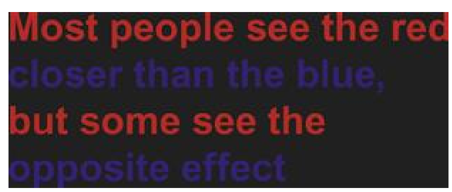

Figure 8: Chromatic aberration

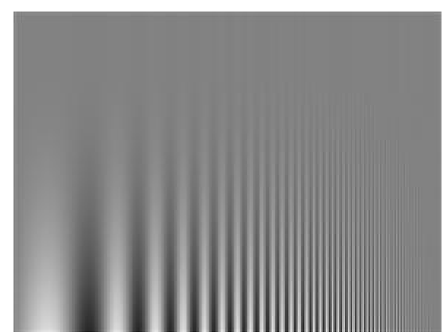

Figure 9: Gradient along a grating pattern

Axon Thousands of photoreceptors (fewer in periphery) $\rightarrow$ ganglion cell, this is a type of neuron and it communicates using an axon. 3% of the visual field receives half of the V1 neurons.

Receptive field area that feeds the retinal ganglion cells.

Brain pixels ganglion cells are the best match. Not uniformly distributed.

Optimal screen There are formulas for calculating efficiency of a screen. Though a typical monitor is only 5% to 10% of our visual field, it stimulates 50% of our brain pixels. Small, high resolution with an interactive program beats low resolution and immersively large.

Parafovea best for pattern perception, 6 degrees, centered on fovea.

Spatial contrast sensitivity Most sensitive to dark bars on grey background at 2 to 3 cycles per degree. At age 80, less sensitive to > 1 degree.

Temporal contrast sensitivity interdependent on spatial. Flicker. Most sensitive between 2 to 10 Hz.

Visual stress striped patterns of 3 cycles per degree, flicker at 20 Hz are the most likely culprits.

Pattern-induced epilepsy Avoid high contrast grating patterns or anything flickering at rates between 5 to 50 Hz.

II.3 The Optimal Display

Dimensions 4000 by 4000 pixels should be adequate. Printers use 1200 dpi, this is to correct for the following two technical and one perception problem.

Aliasing mapping fine patterns to a pixel array causes errors. Our vernier acuity makes use sensitive to these problems. Fixed by computing a type of average of the input data, "anti-aliasing. "

Number of dots the 1200 dpi in a black and white printer are needed to print shades of gray. Aliasing effects are corrected by adding randomness to the dot position, instead of printing in square patches.

Superacuities and displays antialiasing enhances vernier acuity; even if the lines are subpixel size.

Temporal requirements our resolution limit is 50 Hz. Artifacts can be seen if the object moves too fast. Motion blur can fix.

III Chapter 3: Lightness, Brightness, Contrast and Constancy

The eye detects changes in light on a surface, not absolute values. It is also nonlinear in this respect. Can cause errors, not good for categorical encoding. Very skilled at judging *lightness*. Luminance is but one channel, but it its stronger than others, including color (b&w films!).

III.1 Neurons, receptive fields and brightness illusions

Neurons always firing, can be inhibited.

Layers of eye cells $\longrightarrow$ retinal ganglion cells $\longrightarrow$ lateral geniculate nucleus $\longrightarrow$ V1.

Visual receptive field the area over which a cell responds to light. On-center = active neurons, off-center = inhibited neurons. Modeled by DoG model (difference of Gaussians). Two exponential functions, $center - surround$. Edge receptors *laterally inhibit* center receptors.

Hermann grid illusion white intersections seem darker than the white bars between squares because they cause more inhibition.

Simultaneous brightness contrast gray patch looks lighter on a dark background than on a light background. The DoG model shows significant difference in their (relative) brightness.

Mach bands Bright band seen when uniform area meets a luminance ramp. (square gradient). DoG model predicts this.

Chevreul illusion measured brightness = staircase, perceived = upticks as stairs.

Simultaneous contrast and errors grayscale schemes can cause huge perception errors.

Edge enhancement Lateral inhibition can be considered the first step of edge detection. Pseudo-edges can be created by having an edge between them that shades off gradually to two sides. Cornsweet effect. Clear inside/outside. **Haloing**.

III.2 Contrast effects and artifacts in Computer graphics

Black on white is as distinctive as white on black. Only the difference in luminance matters.

Uniform shading vertex uniformly colored based on facet's center's position. Chevreul illusion.

Gouraud shading averages surface normals to shade edges of facets. Mach banding at boundaries.

Phong shading Like Gouraud shading, but surface normal is interpolated between edges. No illusions, very smooth.

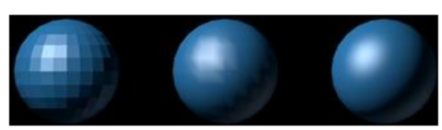

Figure 10: Illusions encountered in Uniform and Gouraud shading.

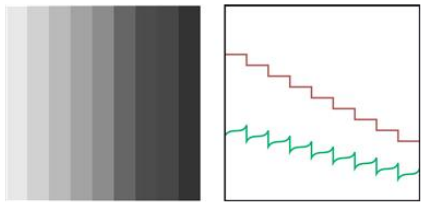

Figure 11: Chevreul illusion, grayscale step patterns

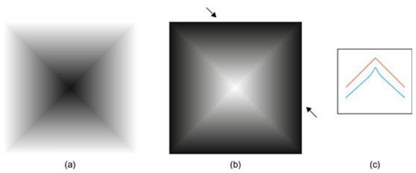

Figure 12: Mach band illusion. Rightmost panel is percevied lightness, calculated wiht DoG model.

Figure 13: Hermann grid illusion. Inhibition may cause the artifacts in the grid intersections

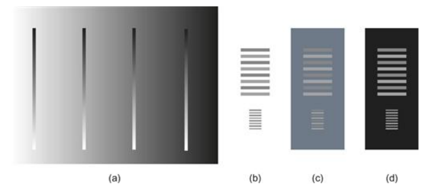

Figure 14: Contrast crispening illusion

III.3 Luminance, Brightness, Lightness and Gamma

Constancy We must know about objects, not light itself. We experience colored surfaces, not colored light. Same for the overall reflectance of a surface. Black paper looks black under any magnitude of light.

Luminance measured (real) amount of light

Brightness perceived amount of light

Lightness perceived reflectance of a surface, its grayscale/saturation.

V(λ) **function** relates the sensitivity of the luminance channel to wavelength. We are about 100 times more sensitive to green light (550nm) than blue (450nm). Red is around 650 nm.

Finer details require greater contrast. Minimum 3:1, text should be 10:1. This limits available colors.

Brightness perceived brightness (of a self-luminous source) is nonlinear related to the amount of light emitted by a lamp.

Sensation $= aI^n$, intensity I. Also applies to other sensations: heaviness, smell, touch.

Monitor gamma pixels emit nonlinear, gamma around 2.0 cancels a brightness power $n = 0.5$ to produce linear perceived brightness.

Lightness constancy Help factor out the effects of amount and color of light. 1. adaptation to available light. 2 lateral inhibition.

Huge range amount of light in a dimly lit room is 10,000 times darker than that available on a bright day. **Photopigment** is bleached at high light levels, regenerates at lower levels.

Simultaneous contrast effect can help us distinguish white from gray even though the two surfaces are on backgrounds of different luminance.

Contrast on paper and on screen pictures are not just their image, but a surface as well! We perceive the actual gray levels of the photographic pigments, as opposed to the gray levels of what is depicted. Contrast illusions are stronger on computer displays. They are self luminous and there is no fine texture.

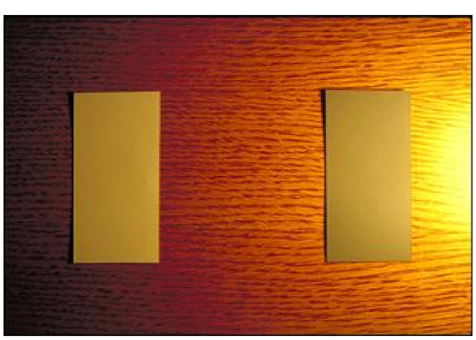

Figure 15: Lightness constancy

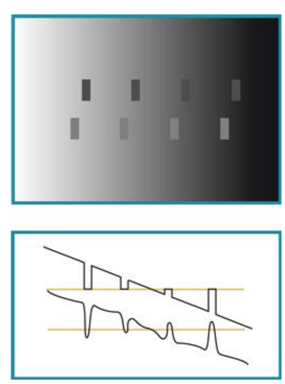

Figure 16: Simultaneous contrast effect

III.4 Perception of surface lightness

The visual system can take into account the fact that a surface turned away from the light receives less light.

We use the lightest object as a **reference white**.

Glossy highlights matter. The most important thing separating an isolated black-world from a white-world is the ratio between specular and non-specular light.

Uniform gray scale bad, don't use. However, it illustrates some general issues related to perceptual scales.

Weber's law For small differences in brightness, the value δ in δL is independent of the overall brightness. Screens only have 8 bit luminance, can't show.

Contrast crispening Another distortion of gray values. Grays near similar gray backgrounds can be differentiated easier (crisper).

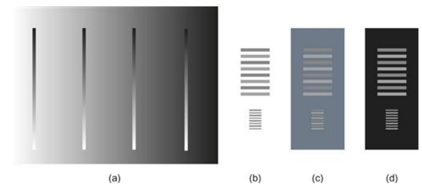

Figure 17: Contrast crispening illusion

III.5 Monitor illumination and Monitor surrounds

Important if accurate color display is needed, like fabric samples on customer's screen, or for an artist's screen. How to setup lightning around monitor?

Ambient room illumination, keep screen emission and room ambience at similar luminance. (Normal: 5% to 20% of screen light is just reflected from room). Really bad with white projector screens.

Contrast reduced when room light falls on display. $L_{monitor} = V^r + A$ where A is ambient illumination, V is voltage, L is luminance output for a given gamma.

Equal voltage steps **= equal perceptual steps**, a lower gamma is needed. Dark viewing conditions = higher gamma.

Room should have a standard light level and illuminant color. The white of the monitor should match the white of a paper help up by screen.

IV Chapter 4: Color

Although color is the most studied feature of perception, the results are few. Most important is opponent process theory. This discussion continues in other chapters.

IV.1 Trichromacy theory

Color vision helped break camouflage. Color is more of an attribute than a primary characteristic. Chickens have 12 kinds of color-sensitive cells.

Color excellent for labeling or categorization. We have 3 kinds of color-sensitive cells. These three colors can be mixed together to simulate other colors.

Cones Rods are overstimulated at most light levels and rendered useless.

Color blindness 10% male, 1% female. Most common is the lack of long-wavelength (protanopia) or medium-wavelength (deuternopia). Respectively, can't see red or green. 3D space collapses to 2D space.

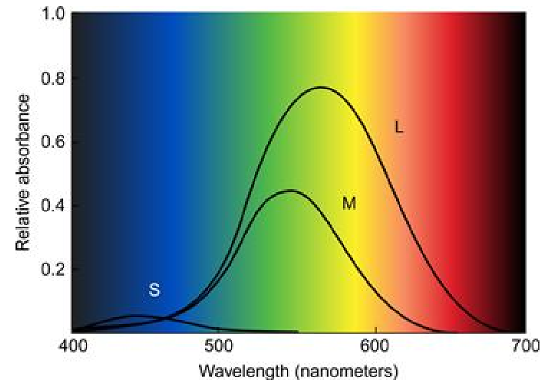

Figure 18: Cone sensitivity functions

IV.2 Color measurement

CIE tristimulus system is the most precise, closest to our perceptive abilities.

CIElab and CIEluv are examples of equidistant color spaces. The same offsets produce the same color differences, unlike in the CIE space.

Useful but even the equidistant spaces cannot be used to predict how a color will be perceived. Thin lines? Hard to distinguish along the yellow-blue.

Gamut 3D figure representing color perception ability in terms of red, green and blue.

Primaries can be mixed to produce any color

Purple boundary connecting red (700nm) to blue (400nm).

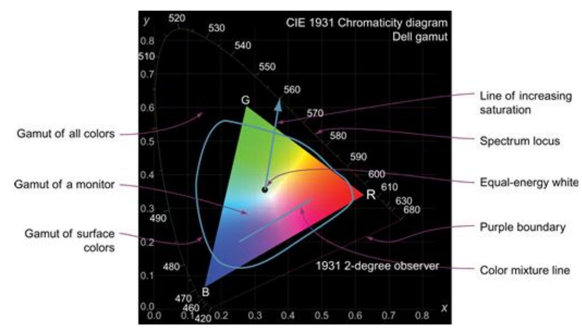

Figure 19: The CIE chromaticity diagram (interesting features)

IV.3 Opponent Process Theory

Opponent-pairs Cornerstone of modern color theory. Black-white, yellow-blue and red-green lie on the same axis.

Naming impossible: reddish green, yellowish blue. Confirmed.

Cross-cultural naming 100 languages! Primary color terms are consistent, first are black and white. Next is red. The fourth and fifth are always yellow or green. The sixth is always blue. Seventh is brown followed by pink, purple, orange, and gray in no order.

Unique hues we can identify yellow to 2nm. Green is either at 514nm or 525nm (for $\frac{1}{3}$ of population). Mostly independent of luminance level.

Neurophysiology Cells in primary visual cortexes of monkeys have the properties predicted by opponent process theory.

Categorical colors colors close to the ideal primaries are easy to remember. Colors that are not basic, like orange or lime green are difficult to remember. Only eight colors and white were accurately named.

IV.4 Properties of color channels

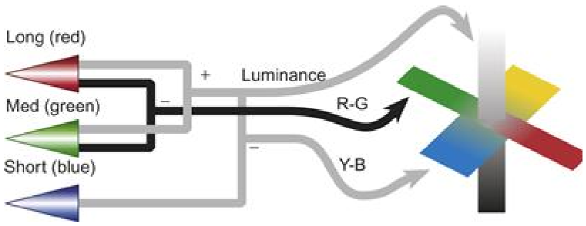

Figure 20: Opponent colors

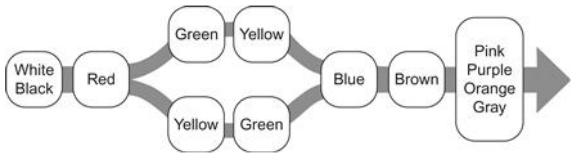

Figure 21: Cross cultural color order

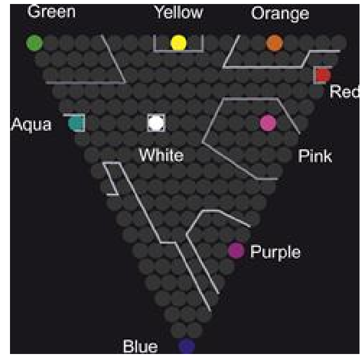

Figure 22: 8 colors identified 75% of the time

IV.5 Properties of color channels

Isoluminant/equiluminous same grayscale. Stereo depth i

Spatial sensitivity the two chromatic colors carry only one-third of the information that the grayscale does. Chromatic differences are not suited for displaying any kind of detail.

Stereoscopic depth only detected using luminance.

Motion sensitivity easier to see the motion of objects with different luminance, colored looks slower.

Form we're very good at perceiving shapes; but if chromatic differences are used for textures, expect weaker looking surfaces.

Summary red-green, yellow-blue inferior in most respects to luminance

IV.6 Color appearance

Monitor surrounds it is important to pay attention to the environment of a monitor, for it affects colors perceived.

Color constancy we cannot see absolute colors, they depend entirely on surrounding colors. Tungsten light is much more yellower than sunlight, but this is not often noticed.

Color contrast similar to lightness contrast (chapter 3), can distort readings of a color-coded map. Relative color is much more important than absolute color.

Saturation high: far from the grayscale, low: dull or grayish. Few saturation steps can be accurately distinguished.

Brown wtf. Dark yellow, but rarely referred to this way. People may need a reference white to see it. May not be distinguishable in a set of color codes.

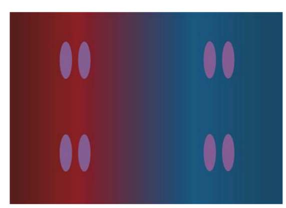

Figure 23: Color contrast illusion

IV.7 App 1: Color specification interfaces

Color spaces design a color picker! Best to offer a method showing colors on different backgrounds.

HSV hue, value and saturation.

RGB red, green and blue.

Color naming People agree on few names. There exist large maps from intuitive names to actual values: NCS, Pantone (USA printing), Munsell (USA surfaces).

Color palettes should provide ability to create personalized palettes.

IV.8 App 2: Color for labeling (nomial codes)

Perceptual factors to consider when picking a set of color labels.

Distinctness uniform (equidistant) color space can be used to determine the difference between two colors. Must also consider background and area.

Unique hues Red, green, yellow, blue, as well as black and white. Small set of color codes required.

Contrast with background should consider different backgrounds. Always make sure there is a luminance difference if symbols must be distinguished from background.

Color blindness Yellow-blue direction is most universal.

Number Five to ten elements can fit in a color code.

Field size Do not use very small color-coded areas. Yellow-blue is hard to distinguish at small sizes.

Conventions Pay attention. Domain specific. Example: hot = red, cold = blue.

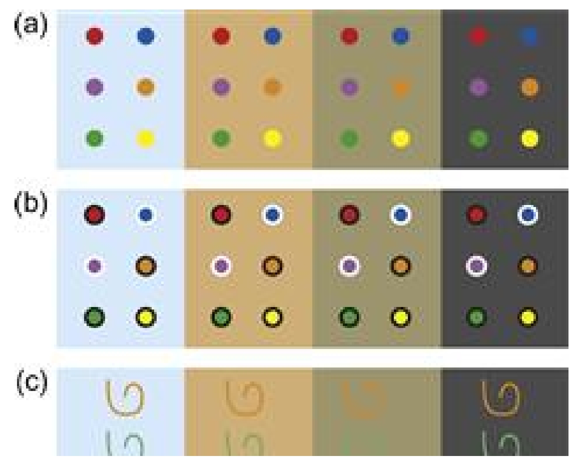

Figure 24: Colors on different backgrounds. Lines especially difficult

IV.9 App 3: Color sequences for data maps

Chloropleth map representing continuous values on a map using color

Form and quantity Different color sequences have different effects when used for ranking. Can be actively misleading. Best to use a straight line through a uniform color space. Could use a spiral sequence.

Interval pseudocolor sequences contours and a discrete sequence of colors (not smooth) work well.

Ratio pseudocolors if values are signed, such a sequence is called diverging or bipolar.

Sequences for the color blind There are specially designed color sequences.

Bivariate color sequences hue and lightness/saturation works well. Don't use color on two axes, they end up unreadable.

Best of the best let a user with enough time decide what shows the most information for them.

IV.10 App 4: Color reproduction

Most output devices cannot reproduce the 16 million colors that can be created by a monitor.

Good mapping from one device to another:

1. White should look white on both devices, same goes for black
2. Maximum luminance contrast is desirable
3. Few colors should lie outside target gamut
4. Hue/saturation shifts should be minimized
5. Increase in saturation is preferable to a decrease

Calibration setup a common reference

Range scaling scale about the luminance axis

Rotation find the neutral white. The two white axes should coalign.

Saturation scaling Scale radially.

Modern printers use heuristics, though an educated technician can do better.

V Chapter 5: Visual salience and finding information

Symbol is an object representing an entity. **Glyph** is a symbol meant to convey one or more numerical attributes of that entity. We mostly see what we expect to see. Glyphs must stand out in at least one channel. For low-level properties, like interferes with like. Channels can be separable or holistic. Must make fundamental design choices and tradeoffs.

V.1 Eye movements

Saccades a fast change of focus. 2-5 per second while reading. Said to be *ballistic*, they cannot be adjusted mid-movement.

Saccadic suppression During such a movement, we are less sensitive to visual input.

Saccadic movements Rapid movement between fixations. Dwell period between 200 and 400 msec. Saccade takes 20 to 180 msec, depends on angle. 2 degrees while reading. 2 to 5 degrees is good.

Smooth-pursuit movements eye can pursue smooth moving objects. Can also make head/body movements to follow.

Convergent movements Also called vergence movements. When an object moves towards us, eyes converge. Moves away, eyes diverge. Can be either saccadic or smooth.

Accomodation refocusing takes about 200 msec. Ability declines with age, fix with different-lens glasses or laser surgery (one near, one far).

V.1.1 What is easily findable?

How do we know where to look next? Heuristics strategy: focus on features that fit our goal most closely.

A priori salience some patterns excite more neural activity than others.

Top-down salience modification Depends on our goal. We can focus on relevant low-level V1 features.

Scene gist Less about feature maps, more experience. Eye movements can be primed to specific types of learned scenes.

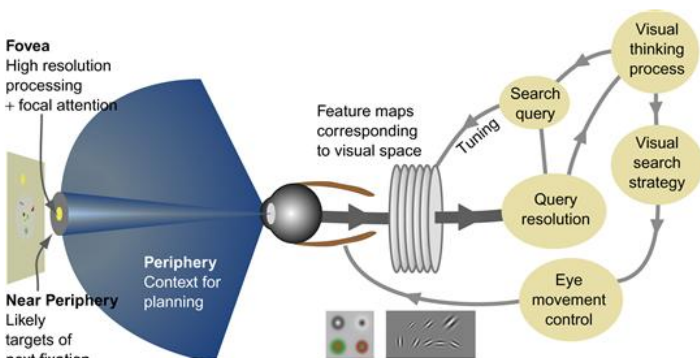

Figure 25: The process of visual search

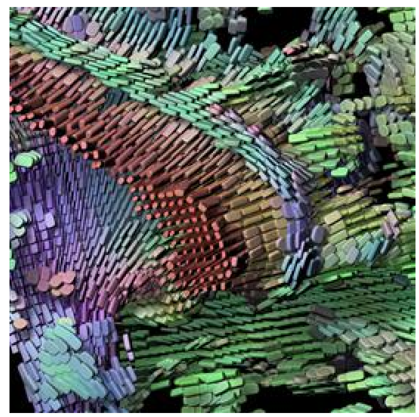

Figure 26: 3D tensor field visualization using color, orientation and shape.

V.2 V1, Channels, and Tuned Receptors

V1 and V2 V1 passes mostly to V2, they represent 40% of vision processing. Several billion neurons devoted to analyzing output from several million nerve fibers.

Optic nerves split the image into red-green, yellow-blue and dark-light channels before sending to V1.

Semi-independent features processed by V1, V2:

1. Orientation and size (with luminance)
2. Color via opponent processing
3. Elements of local stereoscopic depth
4. Elements of local motion

A feature close to another feature is processed by nearby neurons.

Elements of form These features are like phonemes in speech. Can be independent of each other. Color, form and motion. More complex composite patterns aren't processed as rapidly.

Assumption: single neurons can be treated as independent. Groups of neurons or synchronization or temporal spacing also encode information, maybe more?

V1 and V2 continually process orientation and size. Each of the stages has a preferred size/orientation.

Gabor model and visual distinctness Simple mathematical model: multiply a cosine wave by a Gaussian envelope. Excitory center flanked by two inhibitory bars. Variables: amplitude/contrast, size, and rotation. Detect particular orientations but not right-angles.

Barlow's 2nd dogma fits with Gabor model. Simultaneously optimized for spatial location, size and orientation.

Gabor detectors process image in terms of spatial frequency channels. Sub-channels of texture and elements of shape. Orientation sensitivity: 30 degrees. Size: 2x.

Fine discrimination when given more time, people can resolve far smaller differences than with brief exposures. Size: 9%, orientation: 5 degrees. Higher level processes sharpen the output from individual neurons. Common. Operates by comparing *differences* between many neurons.

Point: use size differences, color and orientation to differentiate symbols.

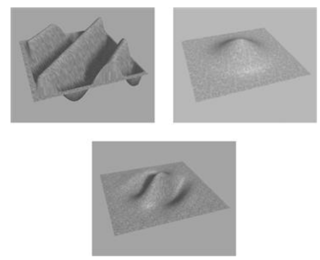

Figure 27: Gabor detector, a sine wave multiplied by a Gaussian envelope

V.3 Pre-attentive processing and ease of search

Preattentive processing captures certain features, entities "pop out." Such features can be detected despite distractors. Misleading name, attention and perception are tightly bound. Anything processed faster than 10 msec. Others are > 40 msec.

Features categorized into form, color, motion, and spatial position:

1. Line orientation
2. Line length, width
3. Size
4. Curvature
5. Spatial grouping
6. Blur
7. "Added marks"
8. Numerosity
9. Color, hue, intensity
10. Motion, direction of
11. Flicker
12. Direction of motion
13. Spatial position
14. 2D position
15. Stereoscopic depth
16. Convex/concave from shading

Attention and expectation subjects can ignore features if unexpected.

Highlight an object by granting it a positively asymmetric preattentive cues, such as color in a black and white field. Subtle motion in static display.

Redundant features can be used for more effective searches.

Not easily findable: conjunction of features. For example: find the red square. Some exceptions:

1. spatial grouping on XY plane
2. stereoscopic depth and color or movement
3. luminance polarity (white on grey) and shape
4. Convexity/concavity and color
5. Motion and anything

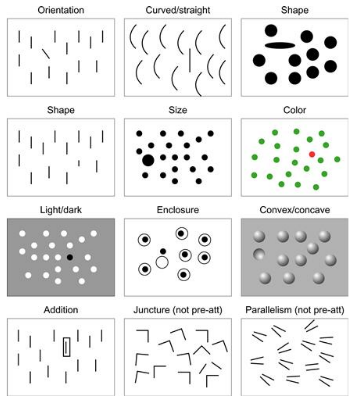

Figure 28: Array of preattentively processed features

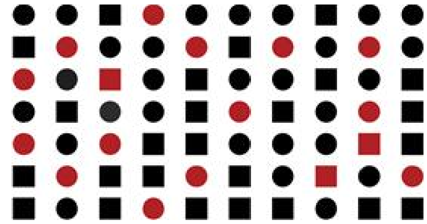

Figure 29: Find the red square

V.4 Integral and separable dimensions. Glyph design.

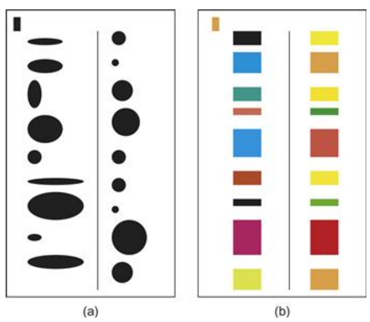

Figure 30: Speeded classification experiments. On height. In (a) the variable width interferes with classification. In (b) the variable color does not interfere

Garner's theory: there are integral and separable dimensions.

Glyph symbols representing quantity

Questions answered: "Will the color-scheme interfere with glyph size?" "Will using both color and size make a variable clearer?" Will displays be perceived independently from each other?

Integral display dimensions two attributes are perceived holistically and not independently

Separable dimensions separate judgments can be made about each graphical dimension.

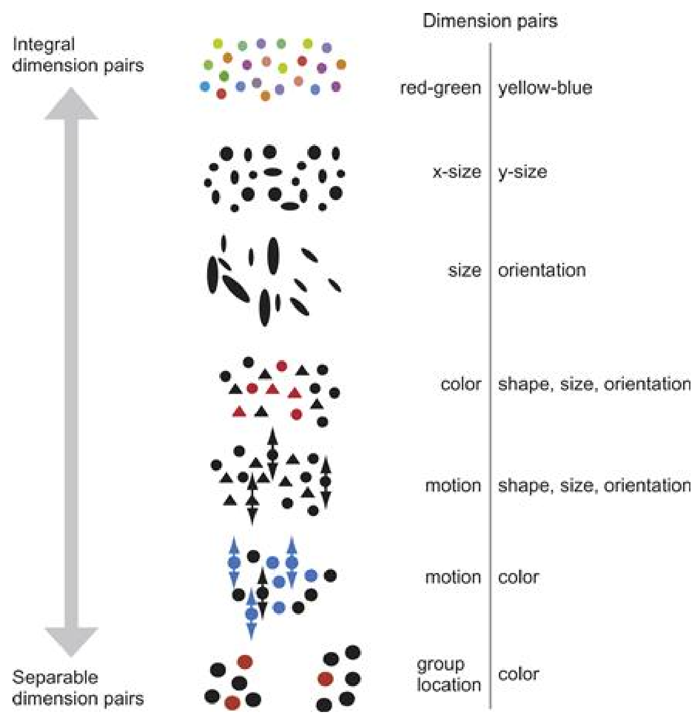

Figure 31: Integral and separable dimension pairs

V.5 Representing quantity

Monotonic visual qualities increase continuously: size, brightness, height. Cyclic: angle, phase of motion, hue.

Ranking height > area > 3D volume > grayscale. Area can convey greater variations.

Exact quantities numerical annotation, bar graph, wind barb (can encode 30 steps, but distort wind direction).

Multidimensional discrete data These are the most useful attributes in glyph design

- **Spatial position** 3 dimensions, XYZ
- **Color** 3 dimensions, color opponent theory
- **Shape** ?, size, orientation are basic, may be more, dimensions are certainly small
- **Surface texture** 3 dimensions, orientation size and contrast.
- **Motion coding** 2-3 dimensions, phase is critical, more research needed
- **Blink coding** 1 dimension, interdependent with motion

Number of resolvable steps is small. Conjunctions are not generally pre-attentive, unfortunately limiting us to about 32 distinct glyphs.

Stars and whiskers No natural mappings to channels? Use whisker/star plots. Each variable is a line emanating from the center. Four whiskers is probably the maximum. Use parallel coordinates in case of multiple data.

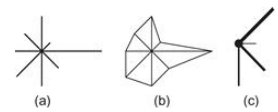

Figure 32: (a) whisker plot, (b) star plot, (c) whisker with four variables and varying width

V.6 Searchlight metaphor and cortical magnification

Searchlight consider the eyeball as an information-gatherer. Information comes in bursts, snapshot for each fixation. Non-preattentive objects arrive at 40 items per second.

Useful field of view we can quickly take information from here. Varies greatly, from 1 to 4 degrees of visual angle for densely populated targets. Can be as large as 15 degrees.

Tunnel vision the UFOV can be extremely compressed under large cognitive load. Consider this when designing user interrupts.

Role of motion in attention UFOV is larger when detecting moving targets. UFOV around 40 degrees.

User interrupts
1. easily perceived, even outside of fovea
2. can be ignored, serve as reminder
3. non irritating
4. can be endowed with varying levels of urgency

Motion as a user interrupt Ship alarm flash patterns: subjects ID'd five patterns with 98% reliability. Motion/blinking are reliable, but can be annoying. Slow motion need not be.

VI Chapter 6: Static and Moving Patterns

What is the best mapping from structured data to the display? How can 2D space be divided into perceptually distinct regions? Under what conditions are patterns perceived similar? Visual connection between objects? Mostly 2D, although some 3D properties are also important. Pattern finding, hooray!

Visual system ranges from massively parallel primitive processing to high level analysis of about one to five objects per fixation. Pattern perception is the middle ground.

VI.1 Gestalt (pattern in German) Laws

A group of German psychologists in 1912 founded the Gestalt school of psychology.

Proximity perceptual organization. Small spacing can have large effects. Consider spatial concentration and small size of fovea.

Similarity similar elements should be grouped. Use channel theory and integral/separable dimensions. Good for independent patterns.

Connectedness overlooked by originals. Connecting by lines.

Continuity Smooth continuous objects are perceived better.

Symmetry so good! Maybe for two time series? Important patterns must be small. 1 degree in width, 2 degrees in height centered at fovea. Don't make it too large. Horizontal/vertical is easier to see. Provide a frame of reference.

Closure and common region Closed contours are seen as objects. Open ones are broken. Great for inside-outside divisions. Venn-Euler diagrams are used during introduction to set theory. Also used in window-based computer UIs.

Clarify closures if they have a complicated shape with a Cornsweet edge, texture or color.

Figure-ground figure is perceived in the foreground. Ground is everything "behind" it. Many Gestalt features help people segment (or not) an image. Closed contour, symmetry, amount of white area all contribute.

Relative size smaller things are more object-like.

Rubin's Vase figure high-level learned face recognition fights mid-level Gestalt figure detection processes.

Common fate a motion based law discussed later.

More on Contours continuous elongated boundaries between regions. Fundamental, receives much attention.

Randomly placed and oriented Gabor patches. Continuity between patches with linear continuity is easiest to perceive. More wiggly patterns can also be detected.

Theory inhibition between neurons with nonaligned receptive fields and mutual reinforcement between neurons with smoothly aligned patches. The winner take-all effect!

Controversial synchronous firing theory neurons firing united may be how the brain retains higher-level patterns. Even if false, there is some neural mechanism enhancing contour detection.

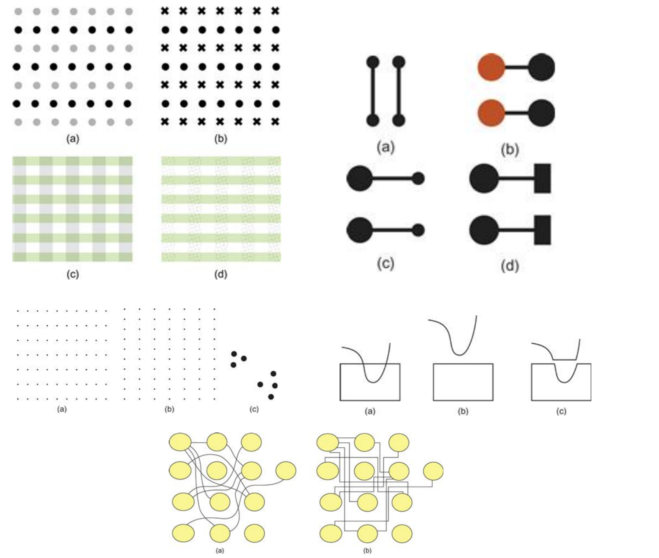

Figure 33: Similarity, connectedness, proximity, and continuity·2

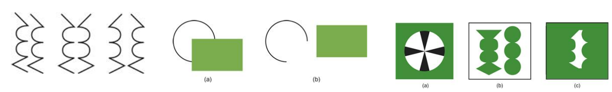

Figure 34: Symmetry, closure, and figure and ground

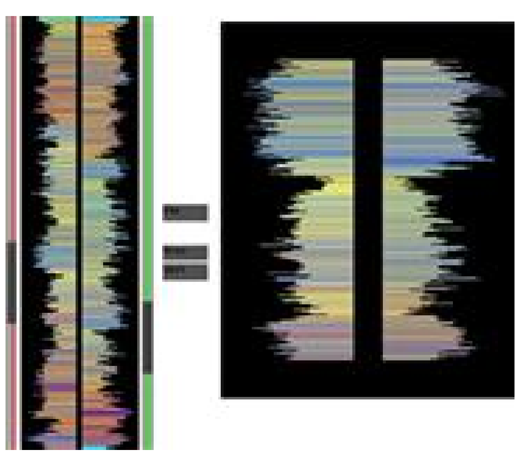

Figure 35: Vis showing similarity in two time series using symmetry.

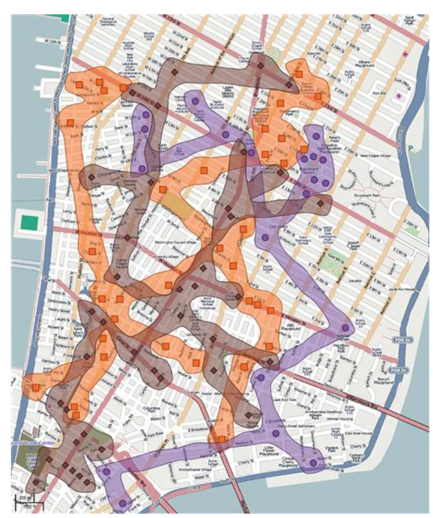

Figure 36: Contour, color and transparency to show distribution of hotels (orange), subway stations (brown), and medical clinic (purple).

VI.2 Visualizing Vector Fields

Perceiving Orientation and direction and magnitude.

Comparing 2D Flow Visualization techniques A head to tail arrangement of vectors is ideal. Continuous contours provide the easiest perception of orientation, but do not show direction or magnitude. Randomly spaced, unconnected vectors are no good.

Tasks during flow visualization are varied and depend on the application. Here are some:

1. Speed, orientation and direction at an arbitrary point
2. Location and nature of critical points
3. Advection trajectory
4. High and low magnitude
5. High and low curl
6. High and low turbulence

Showing direction Plain arrows produce clutter with their contours, their directional asymmetry is weak. It is better to use long narrow airfoils/pen-strokes. Can also vary gray level along the arrow. Called "streamlets." Stronger neural signal = more magnitude.

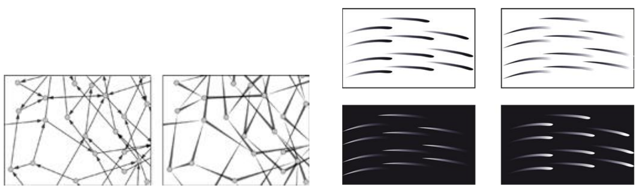

Figure 37: Left: two methods of drawing links, middle is more effective. Right: streamlets, effective for links

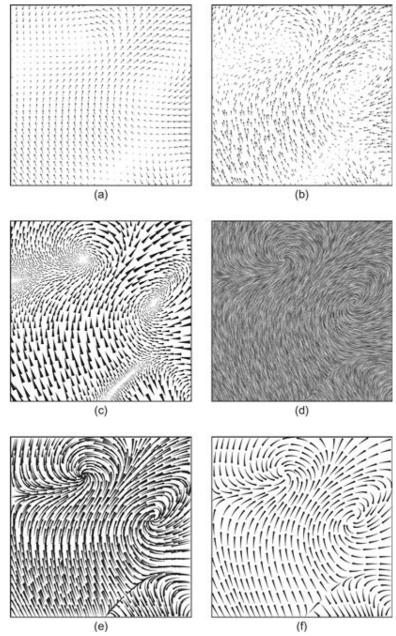

Figure 38: Six different vector field visualizations. Arrows a regular grid, arrows on a jittered grid to reduce perceptual aliasing, triangle icons with size indicating strength (density inversely related to size), line integral convolution, large-head arrows along a stream-line instead of a grid, large-head arrows along streamlines with constant spacing.

VI.3 Texture: Theory and Data Mapping

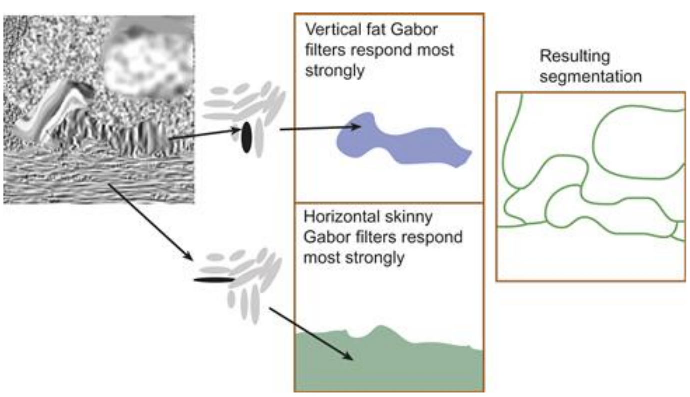

Figure 39: Gabors can explain texture-based segmentation

Texture segmentation regions defined by texture. Independent axis.

Gabor is a Gaussian envelope * sine wave

Gabor filters respond strongly to areas with dominant spatial frequencies and orientations. Contrast of textures is an independent feature.

Feature map consisting of Gabors of different orientation can show primal sensitivity.

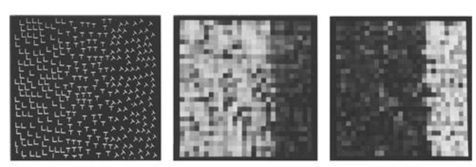

Figure 40: (a) Ts and Ls are difficult to segment, but the leaning Ts can be distinguished easily. (b) feature map of vertical gabors. (c) feature map of oblique gabors

VI.4 Information Density, An Uncertainty Principle

Perception of position, orientation, and size are related by an uncertainty principle.

Orientation can't use size as much

Size less detail can be shown with larger elements

Gabors can be stretched to specify either spatial frequency (size) or orientation more precisely.

Primary dimensions of texture Real Gabors expose many variables, but in our visual systems Gabors with large Gaussians are coupled with high frequency cosine components and same goes for small and low frequencies. Thus a simpler three component model can be proposed:
Orientation: cosine component
Scale: $\frac{1}{spatialfreq}$
Contrast: Amplitude or contrast

Texture contrast effect the same texture overlayed on another appears different. Some textures can interfere with other components, like lines.

Other dimensions the world of texture is much richer than these three variables, though they are dominant. Randomness is also important.

Nominal coding is the most common use for textures. Spatial frequencies should differ by a factor of 3, orientation by 30 degrees; where all other primitive factors are held constant.

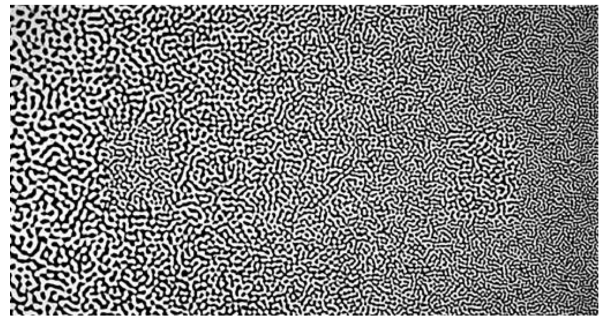

Figure 41: The texture contrast effect. The two patches on the left and right have the same granularity, but the texture contrast makes them seem different.

VI.4.1 Case studies and more texture

Univariate and multivariate Maps Scalars: most common is to vary element size according to the value. Limited because elements must be small to accommodate the data.

Orientes sliver textures for more than one scalar. Sliver contrast indicates magnitude, each dimension has its own sliver orientation. Not readable with many variables.

Attempt two: glyph color (temperature), orientation and direction (wind), glyph area coverage (wind speed), density of elements (pressure).

3, a Scientist and designer: cross-section of a mouse spinal column. Shows 7 variables at each location. Tradeoffs. Glyphs are textured, and end up camouflaged. Worsened by texture orientation. Luminance has the highest range, all other components cause noise and distract from detail.

Quantitative texture sequence 1 10-step texture steps and color. Textures gain luminance. Two maps are successfully combined.

Quantitative texture sequence 2 14-step texture (different shapes, contrast) steps, color, animated streamlet vector field, number labels and a map of the Northwestern USA. Amen! Will need training.

Texture is most valuable if there are two scalar values. To be reasonable, it consumes some luminance channel.

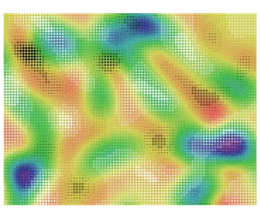

Figure 42: Bivariate map, color and a carefully designed texture sequence

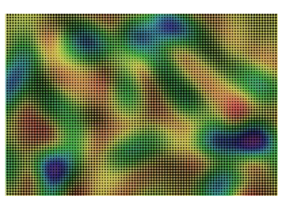

Figure 43: Bivariate map, color and texture element.

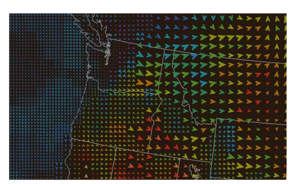

Figure 44: Wind orientation and direction mapped to glyph rotation. Wind speed to glyph area. Pressure is density. Temperature is color.

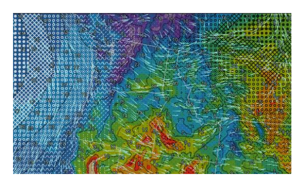

Figure 45: Temperature is color, pressure is a sequence of 14 textures, wind orientation and direction are animated streamlets, wind speed is animation speed and numbers.

VI.5 Perception of transparency

Different layers at the same time common in GIS. The layers will always interfere with each other.

Continuity and color relationships are the most important!

Took longer to read from menu with text or wireframe images as background than one with smoothly shaded images as background.

Laciness as opposed to a single fused image, view each layer through a screen pattern. The effect can be bistable. Asks for tuning because of perceptual interference.

Luminance contrast is needed with texture layered over color-coded data. This constrains the color palette.

VI.6 Perceiving Patterns in Multidimensional Discrete Data

LOTS OF MONEY advertisements and demographics.

Tabulated data is hard to read.

Three dimensions: common to use point size or color or oscillatory motion along with 2D position.

VI.6.1 Higher dimensions

Draw 2D graphs of each possible pairing. Difficult to see higher dimensional relationsips.

Parallel coordinates plot each attribute is a vertical line, a "point" of data is represented by a sequence of lines connecting various vertical ones.

PC plots depend on order of vertical bars, thus it is useful to randomize order and then explore.

PC plots with scatter plots embedded are more useful than draftsman's.

meant to be interactive via "brushing," highlighting the polylines passing through a range.

5D scatter plot, red, green and blue. Color dimensions could be as effective as spatial dimensions when looking for clusters.

Interpreting these clusters can be hard. Greenish = low on red or high in green?

Color can improve PC plots by painting with algorithmially determined color-density schemes.

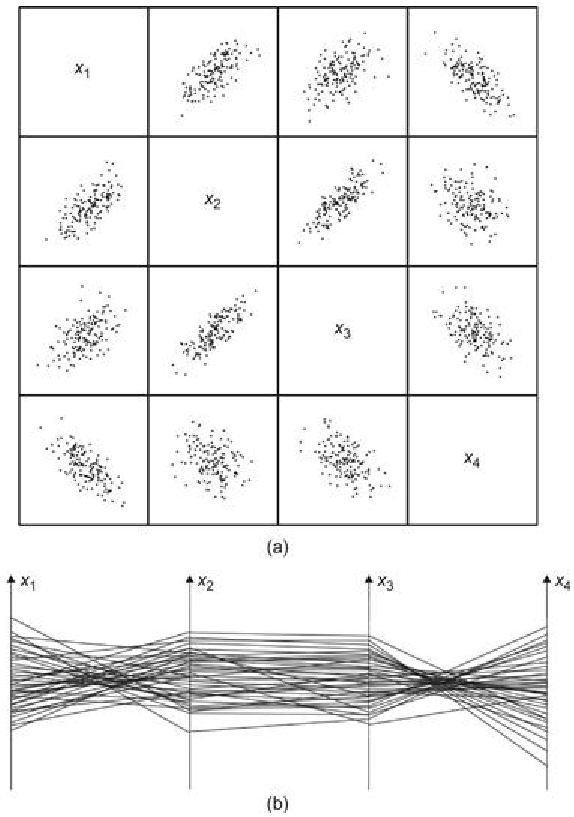

Figure 46: (a) generalized draftsman's plot. (b) parallel coordinates plot.

VI.7 Pattern learning

Low-level features can't be improved much.

Intermediate complexity some learning can occur

Higher-level high level of learning displayed!

Biased experiments a person has seen millions of letters, it would be difficult to improve on that skill. Logarithmic relationship.

Priming transient effects, last minutes to days. Ability to detect certain patterns is improved. It could be visual learning or something less.

Show examples ahead of time

Standards should be relied upon. If your audience has learned certain patterns, use them.

VI.7.1 Vigilance

Some notes about vigilance:

1. Performance falls after the first hour.
2. Fatigue is negative
3. Difficult task requires a high level of sustained attention. No multi tasking.
4. Irrelevant signals are negative
5. Twice as likely to see frequent targets than rare ones.

Can be improved by offering some extra information:

1. target reminders at frequent intervals. Important if many targets.
2. use people's sensitivity to motion
3. the signal must be made as distinct as possible
4. in-place retraining sessions help (bursts of frequent targets)

VI.8 Visual grammar of node-link diagrams

Graph drawing academic field dedicated to readable graphs. Minimize link crossings, structure symmetry, minimal bends in links.

Will analyze node-link diagrams, broader concepth than graphs.

Fundamental argument: closed contours are easily perceived as objects. Our sensory perception provides a scaffolding for even our most abstract concepts.

Interpretations of a countour: ring, flat disk, ball, hole, boundary between two objects (disk in a hole). Convention, context and any Gestalt tell us which is correct.

Closed contour object or entity

Compact shapes entity types

Color of region entity types

Size of region value, larger=more

Majority of diagrams are simple. No variance in shape, size or color. Can show structure but not entity type.

A more varied visual grammar:

Streamlets work good as asymmetric connectors

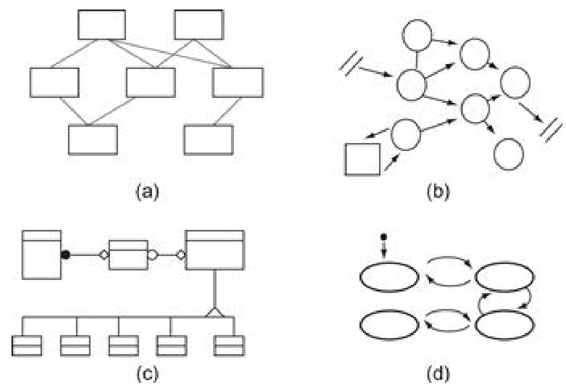

Figure 47: Several node-link diagrams used in software engineering.

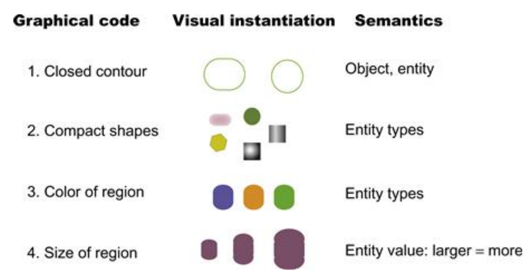

Figure 48: Grammar of a node link visualization.

VI.9 Visual grammar of node-link diagrams

Three graphical marks are common to all maps: areas, line features, small symbols.

Treemap represents tree's leafs. Leafs of lower depth are given more area.

Similar for maps closed contours, colored/textured regions, lines, dots, dot on line, dot in region, line crossing region, line exits region, overlapping regions.

VI.10 Patterns in motion

Pattern detection in motions is not as well understood as other pattern detection systems.

Correspondence problem identical objects may be confused for each other in frames of animation. If the distance between all elements is λ we are limited to a maximum displacement of $\lambda/2$ on each frame.

Wagon-wheel effect they seem to rotate backwards! To show direction, the maximum change per frame should be $\lambda/3$.

60 FPS gives 20 messages per second.

Can be fixed by giving objects different looks. The limit is more like 3λ, or 180 messages per second.

VI.10.1 Form and contour in motion

Relative motion: very sensitive

Motion is an attribute like color or shape.

Phase of motion is perceived best. Comparable to point size or gray value.

elliptical motion can help segment nodes into groups

Moving frames a rectangular frame provides a strong contextual cue for motion perception. A bright frame moved around a bright dot, the static dot seemed to move.

hierarchy the brain groups moving objects in a hierarchy

sensitive to 0.5cm to 4cm per second.

rectangular frames can help highlight local relative motion

expressive motion, motion can express more subtle phenomena

perception of causality elements launch, entrain, trigger other elements. Precise timing is required. Launching occurs within 70ms, delayed launching up to 160ms, after this no causality is perceived.

motion with a biological origin can be detected given the slightest of hints. Random-seeming collection of dots, once animated, became people with gender performing specific tasks. Kindness, fear and aggression can be expressed.

animation can easily expand the information perceived from a diagram.

VI.11 Processes of Pattern Finding

we see what we know but the process of detecting novel patterns is more difficult.

tasks encourage tuning of visual queries. If color is where information lies, then color will be analyzed more thoroughly.

Only a small number of contours can be traced

Attentional shrouds regions of different texture compete for attention. Visual queries allocate attention.

Beyond a certain complexity novel patterns cannot be easily grasped.

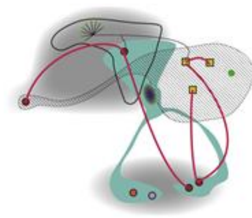

Figure 49: Attend to different components, feel others fade.

VII Chapter 7: Space Perception

Interactive 3D computer graphics are inexpensive, but uneducated designs are ineffective. We are used to the three dimensional, but it does not add much information compared to a 2D display. Motion parallax may be the strongest cue we have, but only in limited situations.

VII.1 Depth Cue Theory

List of monocular depth cues :

1. linear perspective
2. texture gradient
3. size gradient
4. occlusion
5. depth of focus
6. shape-from-shading
7. vertical position
8. relative size to familiar objects
9. cast shadows
10. depth-from-eye accomodation (non-pictorial)
11. structure-from-motion (kinetic depth, motion parallax) (needs moving picture)

List of binocular depth cues :

1. eye convergence
2. stereoscopic depth

Perspective cues :

1. parallel lines converge to a point
2. objects at a distance appear smaller than nearby ones
3. uniformly textured surfaces, where the texture elements become smaller with distance

Size constancy we perceive the actual size of an object instead of its size on the picture. Depth cues can mislead us into finding a difference in size in two same-size elements.

Wrong viewpoint? significant distortions can occur. People can adapt after a few minutes. Can persist during extreme conditions and motion, so it is best if projection parallel

Occlusion Object is either behind or in front of another. Best depth cue, but provides only binary information.

Shading models used in shape-by-shading. Key choice: not realism, but how well is surface shape revealed?

1. Lambertian – computationally easy
2. Specular – glossy
3. Ambient – light from surroundings
4. Cast shadows

Light is assumed to come from above.

Cushion maps treemap with poofy leaf shading, easier to see hierarchy.

Surface texture can provide information about shape.

Draped grid, a simple texture, can help reveal surface shape

Cast shadows form strong depth cues, especially during motion. Fuzzy edges are best, better in uncluttered scenes.

Distance and familiarity objects of known size, arranged meaningfully.

Depth of focus blur is an ambiguous depth cue. Can be properly computed if eye position is known

Eye Accomodation (amount of focus) isn't used as a depth cue

Structure-from-Motion rotation, parallax background, oscillatory motion about the vertical axis

Eye convergence non-optimized geometric calculation, only good at arm's length.

Diplopia double-vision.

Stereoscopic depth small disparities detected in images from two eyes. Diplopia can limit.

Problems with Stereoscopic displays People don't like onscreen. In the real world, double images of nonattended peripheral objects can be ignored. In computers, the lack of depth of focus makes this difficult.

Frame cancellation object is seen in only one eye, or partially so. Acts as an occlusion depth cue, the object seems behind the window, breaks the effect.

The Vergence-Focus Problem (con)vergence of eyes depends on focus The disparity between the focus on the screen and the constant vergence can cause eyestrain. Problem declines with age.

Effective stereoscopic displays Use highest resolution. Screen disparity should be less than 0.03 times the distance to the screen. Can't make absolute depth judgements. Most useful if objects are at 30m or less.

Cyclopean scale to manage diploplia problems. Scale the scene around a center point between the right and left viewpoints; the nearest part of the scene comes to a point just behind the screen.

Virtual eye separation Equations. If VES is smaller than the actual, depth is decreased. However, the brain is imperfect and weighs depth cues differently.

Artificial spatial cues Dropping lines from a floating object to a ground plane. Features are artificially added, but it's a natural depth cue.

Halo around occluding edges of foreground objects. Improves edge contrast, which improves occlusion detection. Good for streamlines.

Proximity luminance covariance "fog." Contrast with background is reduced with distance. *Atmospheric depth*.

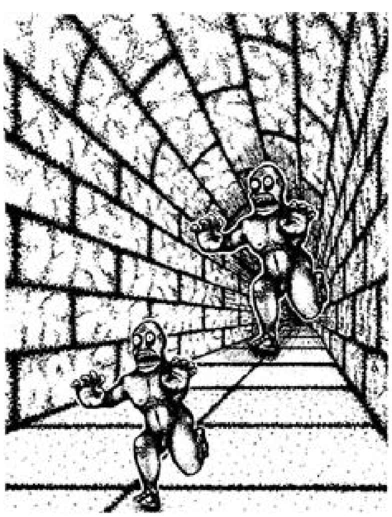

Figure 50: Strong perspective cues distort the size of the figures, though they are the same.

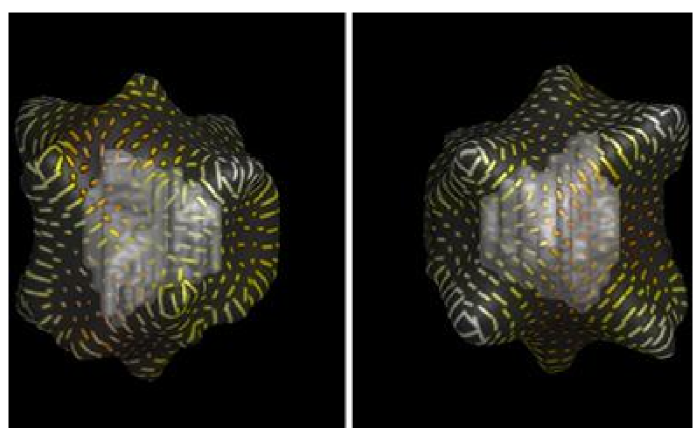

Figure 51: Designed to reveal surface shape so that another surface can be seen beneath.

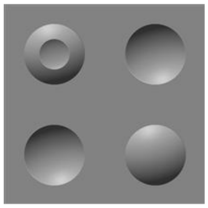

Figure 52: Brain assumes light comes from above

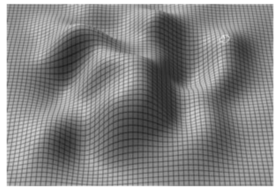

Figure 53: Draped grids can reveal surface shape.

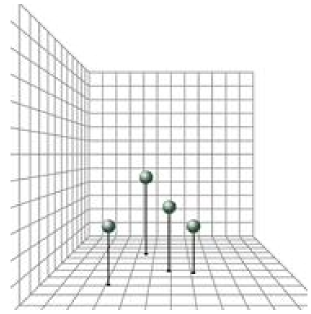

Figure 54: Dropping lines to a ground plane is an effective artifical spatial cue.

VII.2 Combination and Tasks

depth cues in combination people give depth cues different weight, it is not enough to use one type of cue. Combination rules of cues is not a unified theory. Could be ad-hoc, depending on scene

task-based space perception the rest of this chapter is about:

1. tracing 3D paths in graphs
2. judging morphology of surfaces
3. finding patterns of points in 3D
4. finding shapes of 3D paths
5. judging relative positions of objects
6. judging relative movements of self
7. reaching for objects
8. judging "up" direction
9. feeling a sense of presence

VII.3 Tracing data paths

Will 3D structures reveal more data than 2D ones?

Cone trees can display many more nodes than 2D layouts, but the user must navigate to see them

Hyperbolic trees (2D) hide nodes on an exponential scale, it is easier to navigate the tree rapidly.

Path crossings are the greatest source of errors in reading graphs, trees can always be laid out without crossings. Not always the case for node-link structures.

Stereo, head-coupled perspective helped reduce errors with many graph nodes, better than 2D.

Occlusion and halos applied to links can help.

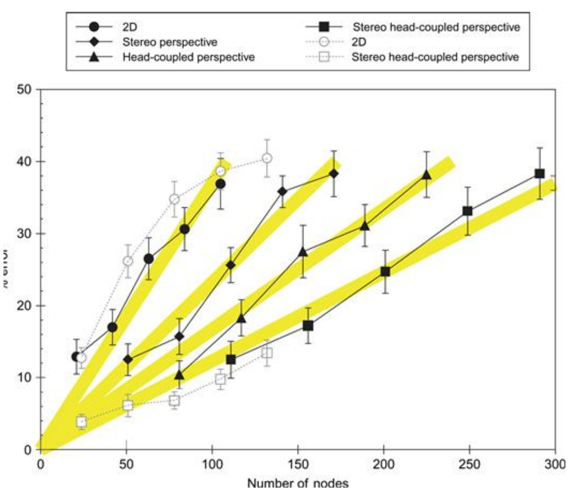

Figure 55: Increase in errors when number of nodes increases.

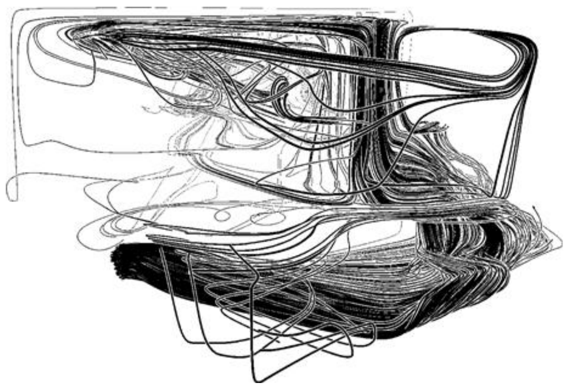

Figure 56: Halos enhance occlusion when objects have the same color or minimal luminance differences.

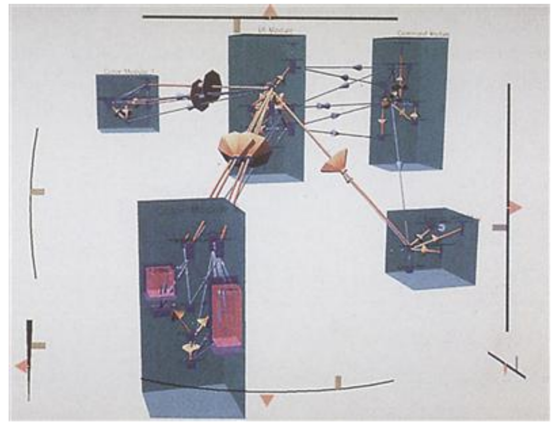

Figure 57: Object-oriented software as a 3D graph

VII.4 Judging morphology of surfaces

Simulating real-world surfaces can help tremendously by leveraging Gibson's affordance theory

Hard to predict who reacts better to different kinds of shading techniques. The best seems to involve stereo and/or motion in combination with any shading (Lambertian or specular).

Conformal textures the same texture contained in different boundaries can give different effects.

Contours can give precise height and supplementary shape/gradient information.

Guidelines A simple lighting model can be more effective, as it models the brain's model more closely than a photorealistic rendering. Motion can decrease time for user to adjust to stereoscopic display.

Bivariate maps Obvious: shape and surface color. Color cannot change rapidly, so it is best to use luminance if the variable changes fast.

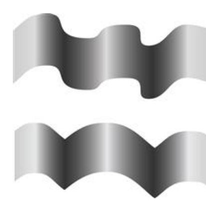

Figure 58: Left to right, these gray values are the same, the contours are the same.

VII.5 Patterns of points in space and in 3D trajectories

Stereoscopic and structure-from-motion are the most effective cues for 3D scatterplots.

Easier to perceive cloud can be formed by treating each point as a flat surface and orienting it using statistical methods. This reveals global shape and shows individual points as well.

Line rendering for a 3D trajectory with motion-parallax or stereoscopic viewing, and occasional drop lines to the ground.

Tube/box trajectory gives perspective and shape-from-shading cues, especially if rings are drawn around the path

Box trajectory may also convey roll information.

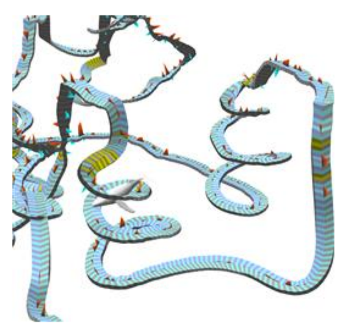

Figure 59: Trajectory of a humpback whale bubble-net feeding shown using an extruded box.

VII.6 Judging relative positions of objects in space, including the Self

Stereoscopic depth plays a minimal role beyond 30m.

Diverse 3D environments make it difficult to make generalized guidelines. It is best to consider all of the depth cues when finding relative positions is important

Self-movement can be simulated using several visual parameters, called *vection*.

- **Field size** larger screen, stronger vection
- **Foreground/background** stronger if background is perceived as more distant
- **Frame** stronger if there is a static foreground between the observer and the moving background
- **Stereo** can help determine if background/foreground is moving, stronger effect.

Simulator sickness caused by conflicting cues between vision and the inner ear.

VII.7 Selecting and positioning in 3D

Reaching for and manipulating objects can be important. It is best to provide a proxy for the user's hand in the simulation.

Effective Depth cues stereoscopic display and motion parallax coupled with head position. The latter seems more important.

Translational offsets are easily adapted to

Rotational offsets are not. Takes weeks to adapt, may not even be complete.

Contact with objects is also important, but difficult to simulate

VII.8 Judging the Up direction and Presence in 3D

This is mainly space research to help people orient themselves in a gravity-free environment

Linear grid on the virtual floor and walls helps

Familiar objects also help

Presence vividly three dimensional. Achieved with a high frame rate and a high level of detail

Stereoscopic display does not help with presence. Provides little extra information.

VIII Chapter 8: Visual Objects and Data Objects

This chapter is far from the concepts of extraction of information from the retina. Once an object is recognized from the set of features, the rest of the brain's systems can process it: visual feedback loops, language, action. Little or no irrelevant information is processed, therein lies the power of human visual thinking.

VIII.1 Image-Based Object Recognition

Image-based object recognition recognition, not recall. We can rather reliably detect objects we have seen before.

RSVP rapid serial visual presentation – pictures shown at 10 per second, people know if a certain object is present

3D objects generally recognized according to same view they were introduced.

Priming even a fleeting meaningless encounter with a visual similar can prepare you to recognize the object again.

Searching an Image Database RSVP could help. Video sped up 64x seems optimal.

Life Logging recording one's life on video is not the same as remembering: it would take much time to recall the details of a truly forgotten event. Can support memory to some extent.

VIII.2 Structure-Based Object Recognition

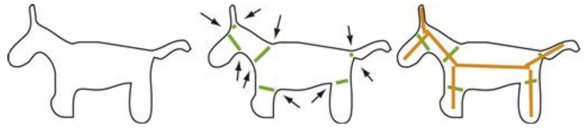

Figure 60: Concave sections define a structural skeleton.

Structure-Based Object Recognition visually distinct 3D views can be recognized as the same object.

Geon theory a hierarchical set of processes: edges, axes/blobs/vertices, finally 3D primitives cones/cylinders/boxes (Geons) are recognized

Geon 3D primitive: cone, cylinder, box, sphere

Silhouettes at some level, these excite the same neurons an actual 3D object does. Canonical views recognized easily. Theory: 2D contours segment image into component solids. Simplified line drawings easier to see than photographs.

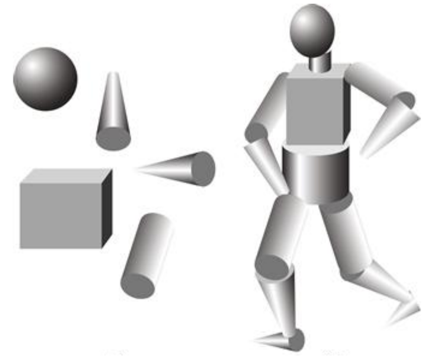

Figure 61: Geons

VIII.3 Object-Based Diagram

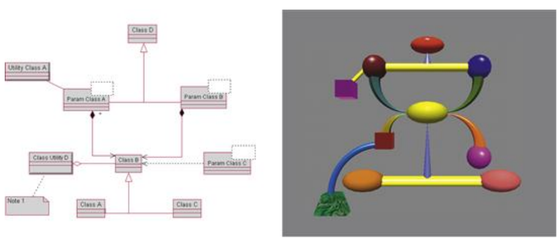

Figure 62: Standard UML diagram on the left vs. a geon diagram representing the same relationships.

Object Display many variables represented as a "single contoured object." Most effective when graphical representations have a natural or metaphorical meaning.

Disadvantage lack generality, object must have meaningful mapping to data.

Geon diagram geons make good elements: color/texture can be attributes.

Faces universally recognized; cannot be generalized to any data or any variable ranges due to emergent expressions generated by some arbitrary points of data. Chernoff faces not in general use.

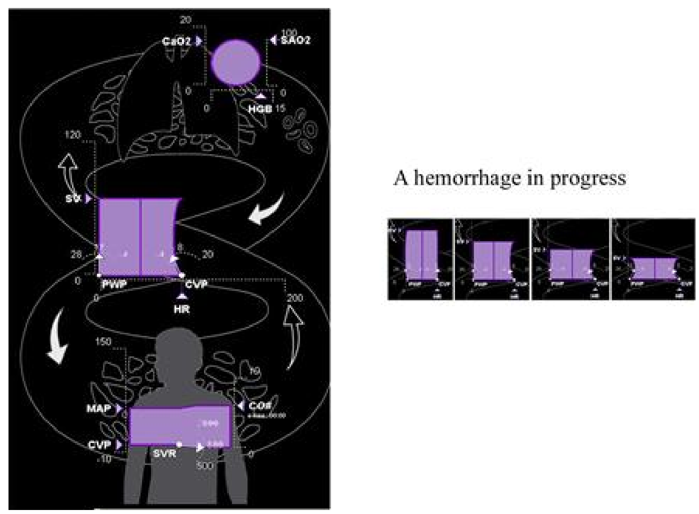

Figure 63: Object-based diagram. Height is volume per heart beat, width is bpm, curving of left- and right-hand sides indicates pressure on left and right sides of heart. Errors reduced by 66%.

VIII.4 Coding Words, Images

Logogens mental representation of language

Imagens mental rep. of visual information

Dual coding theory imagens are separate from logogens

Mental image Imagining and changing the position and size of mental images activates similar neurons. Visual object processing and recognition are part of the same process.

VIII.5 Labels, Concepts

High-level object concepts set of objects labeled with uses, relations, properties. Takes time to develop this network.

Object categorization see spoon: verbal label activated. Object file: links object and its many attributes

Canonical views not all views are equally easy to recognize

Categorical object not all categories can be represented by a simple icon

---

Concept maps nodes are concepts, links are relationships. It is important for students to integrate new knowledge into this network. Can be helpful in communication visualizations.

VIII.6 Icons, Words, Symbols

Symbols can be icons, words or abstract objects.
Pictorial icons best for pedagogy.
Word or abstract symbols: choose based on cognitive efficiency.
Static links integrating text into a static diagram? Consider Gestalt principles.

VIII.7 Scenes and Scene Gist

Rapid categorization occurs with scenes, not just objects. Within 100ms, you know if its a beach, street, interior. . .
Scene gist important because what we see depends on context
Priming positive: improved categorization, negative: alternative interpretations weakened
Trace theory when activity is completed, corresponding neural pathways become strengthened. Faster at automatic classification; less interpretation.

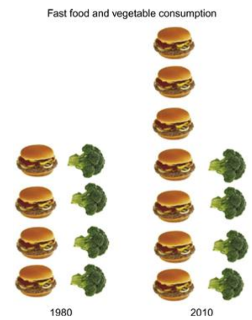

Figure 64: Example visualization using pictorial icons.

Figure 65: Pairs of similar objects with different uses.

IX Chapter 9: Images, Narrative, Gestures for explanation

Most complex visualizations involve visual and verbal material. Exploration, and now a narrative explanation of patterns, have been covered. It is important to make cross-references and use the most appropriate medium. Deictic gestures are the most elementary and fundamental.

IX.1 The Nature of Language

Chomsky's Deep Structures are linguistic featrues that represent innate cognitive abilities based on neural structures.
Sign Language truly visual languages, always with the same complexity as spoken language. Many signs are fully abstract. Language has distinct brain subsytems, activated no matter the medium.
Dynamic and Linear speech, signing, even text are understood as streams of utterances; unlike static pictures which can be understood in parallel.
Visual Programming static diagram system: like learning a new language. Logical constructs are not typically expressed visually, thus it is best to use serial languages for programming.
Images, Sentences, Paragraphs Language: elaborate, complete and widely shared. Images should only be used when necessary. It takes time to process a complex diagram, simple line drawings are fastest to comprehend.
Links between Images and Words theory: it is critical that visual and verbal systems be actively constructed, along with interconnections. Images and words in unison are more effective than either in isolation. Must choose appropriate presentations.

Figure 66: Three sign language representations of a tree. All very different.

IX.2 Integrating Visual and Verbal and the Narrative Thread

Linking Text with Graphical Elements text labels. Also, integrated blocks of text help us retain the information, augment the verbal system's limited memory. Text and figures are typically separated in textbooks – a decline in cognitive efficiency.

Gestures as Linking Devices in verbal presentations. Impossible to look at a diagram and read text, but one can look and listen to a verbal narrative.

Deixis a pointing gesture. Typically used to indicate subject or object in a sentence. Rich vocabulary: can indicate a group of objects, or uncertainty in a region. Web-site: highlighting the image or elements a sentence refers to increases understanding. Help bridge the gap between imagery and speech.

Symbolic Gestures raised hand = stop, wave hand = hello. . . Some gestures represent actions, rotate hand = rotate object, these are called kinetographics. tech like Microsoft Kinect make this affordable, but it is still experimental.

Expressive Gestures hand motion called a *beat* = critical element in narrative. Vigorous gestures = vocal stress.

IX.3 Animated versus Static Presentations

Animated presentations were once claimed to be superior to static presentations. This is false. Animated demonstrations help with short term mimicry; but written explanations, though slower, result in long-term understanding.

This may be because animation hides previous and future images. A static sequence diagram lets the user perform the animation mentally, and only when needed. Thus they are superior.

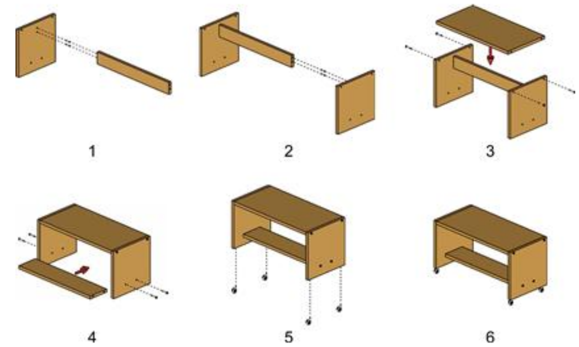

Figure 67: Assembly diagram, employs good design principles

IX.4 Visual Narrative

Visual narrative can be constructed by linear exposition of objects, by camera movements and scene transitions. Like silent movies.

Overview then detail produces more reliable identification than the reverse order.

Anchor a visual reference point. Help link one view of data with the next.

Animated images best if short, otherwise much time must be spent scanning a large animation for a static detail. Hitting, pushing, aggression and most importantly causality can be expressed using dynamic, but not static displays.

Mirror neurons people learn perceptual motor tasks and skills, even become more motivated by imitating others' motions.

X Chapter 10: Interacting with Visualizations

Cognitive systems designers wish to tighten the loop between human and computer. Mantra: "overview first, zoom and filter, then details on demand. Data manipulation loop: lowest level, select and move objects using eye-hand coordination, delays are terrible. Exploration and navigation loop: analyst finding way in a large visual data space. Faster navigation translates to faster thinking.

Main focus is **epistemic actions:** activity intended to uncover new information. Non-static displays. Emphasis is placed on map-like layouts. May not be the optimal layout. Another caveat: we wish to make interfaces transparent to the new user, but expert users may be better off using the (possibly not-optimal) design they are used to.

X.1 Data Selection Loop

Choice reaction time affected by distinctness of signals, amount of visual noise, stimulus-response compatibility. People react faster when allowed to make mistakes. Hick-Hyman law, let C is number of choices, a and b are empirically determined constants in

$$\text{rxn. time} = a + b\log_2 C$$

2D positioning and scaling Time to select a target of particular position and size described by Fitts' law. Describes an iterative eye-hand coordination process. Let D be distance to the center of the target, W be the width, and b, a be empirically determined constants in

$$\text{sel. time} = a + b\log_2(D/W + 1.0)$$

Hover queries Extra information is revealed about an object when the mouse cursor passes over it. A delay is optional. Interactive query rate rise to several per second.

Path tracing continuous control. Let v be the velocity of path tracing, W be the path width and τ be a constant dependent on motor control system

$$v = W\tau$$

2 handed interaction Guiard's (1987) Kinematic chain theory says the dominant performs detailed movements or manipulations, and the frame of reference is provided by the other hand.

Learning practice increases task performance, let T_n be the time to complete the nth trial, a represents steepness of learning curve:

$$\log T_n = \log T_0 - a\log n$$

Control compatibility prior experience with a similar interface can increase learning speed

X.2 Exploration and Navigation Loop

Locomotion and Viewpoint Control Obstacles, margins, brinks, steps, slopes can be used as affordances to encourage and discourage visits. Smoothness is not necessary to detect motion, only identification of relative displacement is needed. Low FPS does cause other problems.

Spatial navigation metaphors good: apt, match the system, easy to understand. Navigation schemes can impose physical limits to the viewport, example: walking limits height seen.

- **World-in-hand** handle on a 3D environment is held and the whole world can be moved.
- **Eyeball-in-hand** user controls a camera. Most effective.
- **Walking** let users walk
- **Flying** relatively unconstrained 3D movement. Actual pilots have difficulty: unnecessary banking while turning, won't stop or go backwards

Wayfinding, Cognitive maps first: landmarks are learned, 2nd: routes are learned, last: cognitive spatial map. Experiment: brief exposure to a map was equivalent to about a year of working in a large building. Overviews should be provided for large spaces.

Terrain features may not be mentally encoded as 3D objects, but as viewpoint-dependent mental images.

Landmarks, Borders, Place in the hippocampus: border cells signal impenetrable barriers, place cells signal specific locations, and grid cells contain updated map of where we are, relative to surroundings. Interesting: subjects provided with 3D overviews of a city's landmarks navigated better than those given pictures or verbal descriptions.

Frames of Reference a map is one of many exocentric views.

Egocentric Frame of Reference our subjective view of the world. Anchored to the head or torso, not direction of gaze. We are accustomed only to pan or tilt, not roll.

Exocentric Frames of Reference God's-eye and wingman's are called tethered because they follow a moving object.

- **Another person's view** someone else's egocentric view
- **Over the shoulder view** behind and to the side of the head of an individual
- **God's-eye view** from above and behind. Common in video games
- **Wingman's view** from the side.

Map orientation Track-up preferable, but experienced navigators or distant collaborators prefer north-up.

- **North-up view** Orthographic. Classical map view. Vehicle in the middle.
- **Track-up view** Orthographic. Heading of the vehicle is the vertical up direction.
- **Track-up perspective view** God's-eye view above and behind the vehicle.

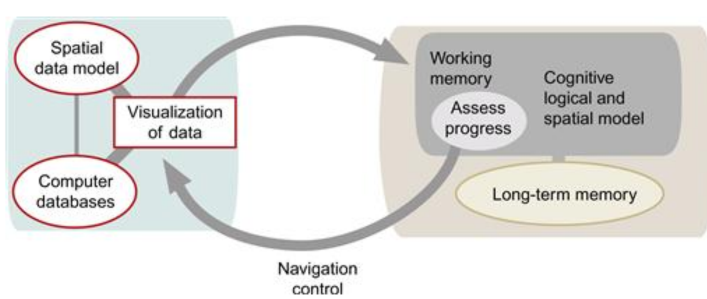

Figure 68: The navigation loop

X.3 Focus, Context, Scale in Nonmetaphoric Interfaces

Focus-context problems Focus is the pattern, which need not be small, context is the larger data landscape.

- **Spatial scale** Information based on real-world scales
- **Structural scale** software example: a single line of code, a subroutine, at the object level, at the system level. Many levels of detail
- **Temporal scale** understanding the timing of events at several scales.

Distortion techniques Hyperbolic tree browser. The fish-eye lens. Some layouts allow multiple foci. Such techniques may render details along the border between focus and context unreadable.

Rapid Zooming Techniques Quick transitions. Ideal rate of zoom is 3 to 4 scale units per second. People vary from 2 to 8.

Key issue how fast can views be changed? Is it smooth enough to maintain identity of objects? Landmarks consistent?

Elision Techniques parts of a structure are hidden until needed.

Multiple Simultaneous Views large data space? One window shows an overview, and others show expanded details. Link the windows w/ Gestalt principles.

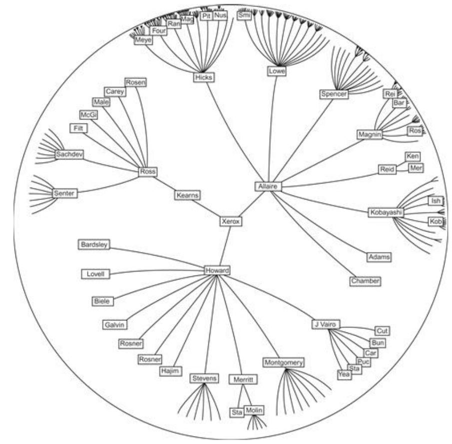

Figure 69: A hyperbolic tree. Far away nodes are clicked to focus on them.

XI Chapter 11: Visual Thinking Processes

Foraging for food has much in common with foraging for information. Both must be done efficiently, often there are large gaps between finding succulent food or information clusters. There is also a scent indicating where these may be.

The common bottleneck in visual thinking is our limited working memory capacities. This is why rapid attention shifts must be made possible.

In this new field, there is still much to invent and improve. As the years pass, these innovations will become standards for information professionals; like clay hardening in the kiln.

XI.1 Cognitive System

We will focus on **epistemic actions**, simple ones triggered by the user where rapid transformations change what is presented.

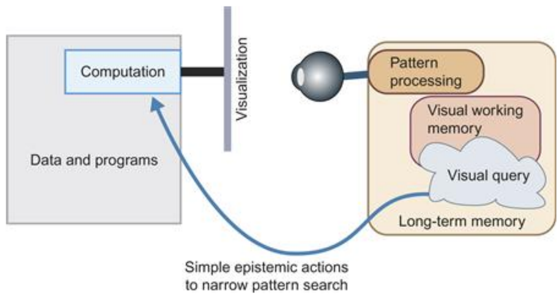

Figure 70: The system considered in this chapter.

XI.2 Memory and Attention

Iconic memory short-term, holds retinal image for a few hundred ms or until replaced, no semantics

Visual working memory (VWM) holds objects of immediate attention, usually a combination of images and semantics from long-term memory

Long-term memory everyday use, may last a lifetime, tight links to working memory

Working memories separate systems for auditory, visual information; also body movements, verbal output. There may be more for cognitive instructions and motor control. They are mostly independently.

Visual working memory capacity position, some abstract shape, color, texture are retained from one fixation to the next. Limited to three to five simple objects. Example: simple mushroom stem and cap count as two objects. Integrated glyphs allow more info to be held.

Change blindness we don't see the world's complexity and detail at the same time! It only seems that way because of our long-term memory (provides gist) and details are there when we want them. Experiment: people failed to notice when their new partner was swapped mid-conversation.

Spatial information possible to store up to nine ego-centric locations. Separate from retinal locations. Can hold three to five moving objects across fixations.

Attention to hold three to four objects in VWM takes a lot of attention. Inattentional blindness is possible: i.e. an unexpected pattern appears and test subject doesn't notice it. Attention's selectivity isn't perfect, see the Stroop effect.

Object files, coherence fields, gist Object files in Chapter 8. Gist: verbal-propositions recalled by images from long-term memory within 100ms. Typical locations, general information remembered.

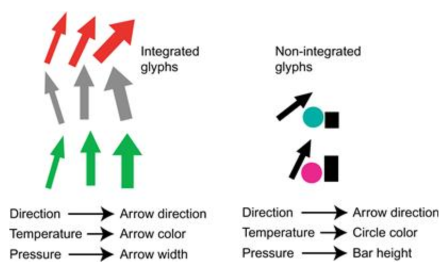

Figure 71: Integrated glyphs allow more information to be held in visual working memory.

Figure 72: Stroop effect: the colors of the lower set of words cannot be easily spoken in sequence.

XI.3 Long-term memory

Long-term memory built up over a lifetime. Includes verbal material, motor skills, perceptual skills. Not all of it is conscious.

Episodic memory memories associated with events.

Hippocampus appears to form long-term memories.

Memory trace theory memories are traces – neural pathways made of strengthened connections. Explains priming and recognition > recall.

Chunks and concepts interchangeable terms here. The grouping of objects into more complex ones. Expertise = effective high-level concepts.

XI.4 Knowledge formation, creative thinking

Bayesian approach learning done through repeated exposure, neural pathways strengthened.

Physicalist theory new concepts built on top of old ones. Single event learning of new concepts.

Teaching hill climbing problems can be solved by using simulated annealing (controlled randomness, metallurgic term). Students saw visualization of red dots bouncing on terrain with local min and absolute min. With increased randomness, the dots avoided the local min.

Results students had to solve a similar problem. Finding a path through obstacles can be accomplished with similar simulated annealing.

Knowledge transfer deep learning. (Animations shouldn't be too concrete) Formed by a kind of hypothesis-testing mechanism.

XI.5 Visualizations and Mental Images

Diagrams can be built mentally, without external aid. Properties of mental images:

Transitory fade without cognitive effort

Simple images only, for most people

Few items can be imaged

Aggregations are easy

Operations can be performed

Logical problems can be solved with mental images

Same neural machinery as normal seeing, to some extent

Can be combined with external imagery. Labeling, additions, deletions, other modifications possible. This is a key skill for hypothesis formation.

XI.6 Review of Visual Cognitive System Components

These systems are needed in the construction of visual thinking algorithms.

Early visual processing Motion, color, texture/shape. Two to four categories per channel rapidly perceived.

Pattern perception From contours, areas of texture, color, motion. A few simple ones held.

Eye movements Planned using spatial map of proto-patterns. Partial solutions marked in egocentric map.

The intrasaccadic Scanning loop simple visual shape, processed at 40msec.

Working memory three to five items. Attention controls. Part is a rough egocentric spatial map.

Mental imagery our ability to build simple images in mind.

Epistemic Actions to discover information.

- **Attentional switch** 50ms, minimal cognitive effort
- **Saccadic eye movement** 150ms, minimal
- **Hover query** 1s, medium
- **Selection** 2s, medium
- **Hypertext jump** 3s, medium
- **Zooming** 2s + log change, medium cognitive effort
- **Virtual flying** 30s, high
- **Virtual walking** 30s, high cognitive effort

Visual Queries hypothesis related to cognitive task. Solved by epistemic actions.

Computational Data Mappings many ways to turn data into pixels. Principle of transparency: the user can apply intellect to the task, the tool itself seems vanished.

XI.7 Visual Thinking Algorithms

In each, the interplay between information and operations will be considered:

Perceptual and cognitive operation. Anything occuring in the person's brain

Displayed information represented by the visualization.

Epistemic actions actions designed to seek information

Externalizing someone saves knowledge by putting it in the world

Computation parts of the visual thinking algotihm executed by computer

XI.8 Algorithm 1: Visual Queries

Visual query like a subroutine, components of all visual thinking algorithms. A pattern is first cognitively specified, looked for in the display, and if found, contributes to the solution of a problem.

Most important factor is the use of preattentive features for speed. Experience also helps a user's speed.

Display environment a graphic display containing potentially meaningful visual patterns.

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1. Problem components identified that have visual pattern based solutions. A visual query is formulated to discriminate between anticipated patterns.
2. Low-level visual system is made sensitive to these patterns. Visual scan begun vased on knowledge, display gist, and task.
3. Eye movement made to the next best location based on space map, gist, prior location knowledge.
4. Search targets in fixation processed at 40ms per item. Tests are run on patterns and objects elicited from proto-patterns and proto-objects.
5. Repeat from 3 as needed. Only a simple description of object and pattern components is retained in VWM. Small number of cognitive markers placed in spatial map as needed.

XI.9 Algorithm 2: Pathfinding

Trip planning also applies to navigating a network diagram

Visual query construction city locations are primed, but not kept in VWM.

Pattern-finding loop A path can use up the entire VWM. Cognitive labeling helps us reconstruct alternate paths or chunks of a path.

Display environment road map with symbols representing cities, colored lines are roads. Can also be node-link diagram.

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1. Conduct visual search to find start and end points.
2. Mark these in mental map
3. Find start symbol. Extract patterns relating to particular color that trend in right direction. Mark end point symbol of best candidate line.
4. Repeat 3 using a new start point until the destination is reached.
5. Push path info into logical proposition store. Little info needed, easy to reconstruct.
6. Repeat 3 to find alternative paths, avoiding paths already found.

XI.10 Algorithm 3: Hybrid Reasoning: Visual and Mental Imagery

Some reasoning is well supported by visual operations, thus a mental image is helpful.

Display environment a diagram or other vis representing part of the solution to a problem

1. Perceive task-relevant patterns, mentally add semantics.
2. Imagine display modifications.
3. Execute visual queries on the combined internal/external image to solve the problem

XI.11 Algorithm 4: Design Sketching

Similar to Algorithm 3 now imagined modifications are externalized

Better it allows more creativity, easier to change and share

Architects use sketches liberally in their design process

Display environment Paper and pencil or table computer

1. Imagine some aspect of design
2. Put marks on display to externalize aspects
3. Analytic visual queries to determine if design meets requirements
4. Major flaw? Discard sketch
5. Imagine additions, or reattribute meanings of symbols
6. Visual queries to asses value of imagined additions
7. If acceptable, add marks or erasures
8. Repeat from 5, revising. Repeat from 1, discarding.

XI.12 Algorithm 5: Brushing

Brushing selecting a data object in any view causes it to be selected in all other views.

Highlighting methods MUST support fast search. Try motion if displays are crowded.

Display environment data objects represented in at least two different displays

1. Visual query requiring info about a subset of data
2. Select symbols representing relevant subsets
3. Execute visual queries for patterns in the highlighted representation. May require info from two or more displays, can be limited by VWM.

XI.13 Algorithm 6: Small Pattern Comparisons in a Large Info Space

Multiple windows Focused details have linked windows.

Zoom interface comparisons made through rapid scale changes. Better to use this if the master pattern fits in VWM.

Rough cost time = setup + number of comparison queries

Display environment

1. Epistemic action: navigate to location of the first pattern.
2. Retain subset of pattern in VWM.
3. Epistemic action: navigate to candidate location of a comparison pattern.
4. Compare VWM with candidate. If suitable match found, terminate the search. If partial navigate back and forth the two patterns, comparing different subsets to each other.
5. If mismatch, repeat from step 1. Mark already-evaluated candidate locations.

XI.14 Algorithm 7: Degree-of-Relevance Highlighting

Related objects may become distributed across the display.

Degree of relevance highlighting: when an object is selected, all related objects are highlighted as well.

Useful for 30 to thousands of objects. Very effective if the ranking function can filter highlighted objects to 10 or 20 objects.

Display environment display containing many symbols linked by complex overlapping set of relationships

1. Construct visual query to find a symbol with potentially useful information ("scent").
2. Epistemic: select symbol.
3. Computer highlights all symbols with a high degree of relevance to this symbol.
4. Visual pattern query for more information "scent"
5. If high relevance symbol is found, execute addition epistemic action to find more info. Usually shown in another window.
6. Repeat from 1 as needed.

XI.15 Algorithm 8: Generalized Fisheye Views

Beneficial with hierarchical data. Removes clutter by hiding irrelevant elements.

Downside important information is hidden

Degree of relevance function determines what is shown and what is not

Display environment a set of symbols representing entities from a much larger set. Entities linked by complex overlapping set of relationships

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1. Visual query to find info accessible via particular symbol. Conduct search.
2. Epistemic action: select symbol.
3. Computer displays all symbols representing data above computer relevance threshold. Can weigh so that most salient displayed with most detail. Irrelevant symbols are hidden.
4. Visual query to find info in updated display.
5. If high relevance symbol is found, execute addition epistemic action to find more info. Usually shown in another window.
6. Repeat from 1 as needed, mentally marking locations of visited symbols.

XI.16 Algorithm 9: Multidimensional Dynamic Queries with Scatter Plot

Multidimensional discrete data all entities have the same set of attributes.

Dynamic queries control the entities on the display. These are implemented as slide bars for each attribute.

Not just scatter plots can also apply to parallel coordinates.

Display environment a scatterplot with symbols representing entities drawn from a set of multidimensional discrete data, with a set of controls restricting range displayed on each data dimension.

---

1. Visual query addressable by viewing a subset of discrete data defined by a hyperbox is constructed
2. Query is executed. Is the number of targets small enough for the required perception? Is the pattern found?
3. If high relevance symbol is found, execute addition epistemic action to find more info. Usually shown in another window.
4. Execute an epistemic action to change displayed subset by dragging a slider that causes the computer to adjust a range on a data dimension.
5. Repeat from 2 until task is successful or abandoned.

XI.17 Algorithm 10: Visual Monitoring Strategies

Supervisory control a system runs on auto-pilot, with occasional input from a human operator. Anomalous patterns need to be perceived and corrected.

Typical elements built to account for operator's visual scanning strategies:

- **Channels** different ways in which information can be received. Channels can be display windows, dials, loudspeakers...
- **Events** signals occurring
- **Expected cost** of missing an event

Visual scanning patterns influenced by minimized eye movements (two operators within same effective FOV can help). Also by oversampling of channels on which infrequent information appears (fixed by operators sampling more frequently than required).

Reliabilty Improved by occasional visual or auditory reminders: such as motion which allows different levels of urgency.

High-stress situations? Hide or dim unnecessary channels in case of dire emergencies.

Display environment a set of glyphs representing status of various system components.

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1. Setup a cognitive self-interrupt schedule.
2. When an internal cognitive interrupt occurs, scan display with eye movements. Test each component for patterns requiring action.
3. If such a pattern is found, take action.
4. Repeat from 2 as needed.

XII Visualization Guidelines

XII.1 Chapter 1

Foundation for a science of data visualization.

1. Design graphic representations of data by taking into account human sensory capabilities in such a way that **important** data elements/patterns can be **perceived**
2. Important data should be visually distinct (which items are more findable?)
3. Visual distinction should match the data's magnitude
4. Graphical symbols should be **standardized** within and across applications
5. Choose the tool that allows for the most work per time, **save time**
6. Novel solutions are good if they outweigh the **cost of learning**
7. Unless novelty outweighs inconsistency, pick consistent tools
8. Effort spend on development should equal expected "profit"

XII.2 Chapter 2

The environment, optics, resolution and the display

1. **Lambertian** shading to reveal shapes of smooth surfaces
2. Use **specular** shading to reveal fine surface details. Object/light motion should be enabled.
3. **Cast shadows** for large-scale spatial relationships. Do not use unless the visual cost is made up for in benefits.
4. Ambient **occlusion** for 2D shape perception, where no shading info is provided.
5. Agumented-reality: info linked to an external object should be at the **same focal distance**
6. Augmented reality: if info is unrelated to externals, the aug-info should seem **closer than everything**
7. Head-mounted display: text should be no more than **18 degrees**
8. **40 degree** viewing angle for data analysis
9. wrap-around displays to give a sense of "presence"

10. Avoid high-contrast grating patterns, especially if flickering between **5Hz and 50Hz**.
11. **Antialias** whenever possible, especially if there are fine details

XII.3 Chapter 3

Lightness, brightness, contrast, constancy

1. **Avoid gray** scale as a method for representing more than 2 – 4 numerical values
2. Consider using **cornsweet contours** instead of simple lines to define convoluted (crazy) bounded regions
3. Consider using **luminance contrast** as a highlighting method. Either reduce contrast of unimportant items or increase local background's contrast around important items (haloing).
4. Use minimum **3:1 luminance contrast** ratio when details such as texture variation, small-scale patterns or text exist. 10:1 is optimal for text.
5. If **subtle grey-level** variations are important, create low-luminance contrast between object and its background.
6. A light neutral colored wall **behind the screen** should reflect an amount of light comparable to that emitted by the screen. The wall facing the screen should be dark and of low reflectance. Avoid shining lights on the monitor.
7. Minimal light should fall on the projector screen. **Shields**, low-reflectance (mid to dark gray) walls are desirable.

XII.4 Chapter 4

Color

1. Use more **saturated colors** for small symbols/lines/areas. Less saturated for larger areas
2. Small symbols with a color different from the background's should have a **luminance contrast** (See 3.4)
3. Adequate luminance contrast for the perception of **stereoscopic depth**
4. Adequate luminance contrast for the perception of **motion**
5. If shading to define a **curved surface**, use luminance instead of chroma. (See 2.1)
6. If large areas have equiluminous coloring, use **thin borders** with large luminance differences
7. Saturation should be used to encode **no more than 3** values
8. Red-green, yellow-blue, white-black are independent.
9. In an interface for design, allow the user to **change background** to see effects on coloring
10. Easy-to-remember color codes: provide a **color palette**
11. Pure red, green, yellow and blue to color code **small symbols**.
12. Small color-coded symbols: ensure **luminance and chromatic** contrast with background
13. Colored symbols isoluminant against parts of background? Add a **border** with a highly contrasting luminance (relative to symbol).
14. To ensure color-blind accesibility, use **yellow-blue** variance.
15. **No more than 10 colors** if precise identification is desired, especially if varying backgrounds.
16. **Low saturation colors for large** areas. Light colors are best, more of these available.
17. Large backgrounds overlaid with small colored symbols? High-value/**pastel colors for background, high saturation** for symbols
18. If text is highlighted, ensure **luminance contrast** with background.
19. Cultures have a **similar high-importance color** sequence, varying low-importance. Consider this in maps.
20. If extremes or other patterns must be seen, use a color sequence with **monotonically increasing luminance**. Carefully space colors if discriminate steps are wanted

XII.5 Chapter 5

Visual salience and finding information

1. Minimize the cost of visual searches by making displays as compact as possible. **Saccades of 5 degrees** or less.
2. Visually distinct aspects should be represented by **distinct channels**.
3. Symbols should be **distinct from background and other symbols**, if search is needed.
4. Make symbols as **distinct from each other** as possible; orientation and spatial frequency (size difference).
5. Same for symbols and background patterns.
6. Strong preattentive cues **before weak ones** if search is critical.
7. Maximum popout: a symbol should be the **only object in a channel**
8. **Asymmetric preattentive** cues for highlighting
9. Highlights should occupy the **least used feature dimension**.
10. Use **subtle blinking or motion** if color and shape channels are full.
11. Use **redundant coding** where possible
12. If symbols are to be preattentively distinct, avoid using **conjunctions** of graphical properties.
13. If two distinct attributes must be highlighted, consider using motion and color/shape or another **valid conjunctive pair**.
14. If variables need to be seen holistically, map the variables to **integral** glyph properties
15. If variables need to be seen analytically, map the variables to **separable** glyph properties
16. **Quantity** shown by size, lightness on a dark background, darkness on light background, color saturation, vertical position
17. Ideally, use **length or height** to represent quantity; maybe area. Never use 3D volume.
18. Combine heterogeneous display channels with meaningful **mappings between** data and graphical features
19. User interrupts must be made stronger if **cognitive load** is high.

XII.6 Chapter 6

Static and moving patterns

1. Symbols with related information should maintain **proximity**
2. Grid layout = low visual channel properties for **rows/columns**.
3. Use lines or ribbons of color to show **relationships**.
4. Use symmetry to make pattern comparisons easier, be sure patterns are > 2 degrees horizontally, and > 1 degree vertically. Symmetry should be along horizontal/vertical axes.
5. Related information inside a **closed contour**.
6. **Overlapping regions** = combine line contour, color, texture, Cornsweet contours.
7. Combination of closure, common region and layout to ensure data entities represented by patterns will be **figure and not ground**.
8. Use contours **tangential** to streamlines to reveal orientation.
9. Flow direction in vector field = use **streamlets**.
10. **Vector field** = more distinct elements indicate greater strength or speed. Wider, longer, more contrasting, faster moving.
11. **Texture for continuous** map variables. Most effect when data varies smoothly.

12. To make nominal coding textures **distinct**, make them differ as much as possible in orientation and element size. Also vary randomness in spacing of elements.
13. **Simple texture** parameters such as element size/density only when fewer than five ordinal steps must be distinguished
14. **Bivariate scalar** field? Map one to color and one to texture variations.
15. Design textures so quantitative values can be judged? Visually order so that **small** can be differentiated from **large**.
16. When using overlapping textures to separate overlapping regions, avoid patterns that can cause **aliasing** when combined
17. Textures in combination with background colors in overlapping regions? Use **lacy textures**.
18. Lacy textures in combination with colors for **overlapping** regions. Ensure luminance contrast between texture in foreground and color-coded data in background.
19. Discrete data with more than four dimensions? Use color-enhanced generalized **draftsman's plots with brushing**.
20. **Standardize mappings** of data to patterns within and across applications.
21. Search for infrequent targets? Insert **retraining sessions** and give feedback on failure/success.
22. Glyphs = small enclosed **shapes** for entity. **Color, shape and size** for attributes.
23. Connecting **lines, enclosure, grouping and attachment** to show relationships between entities. Shape/color/thickness for types.
24. Alternative to arrows in directed graphs = **tapered lines** with broadest end at source node.
25. Use **closed contours**, areas of texture or color to denote regions. Color/texture/boundary style to show type.
26. Use **lines** to represent paths. Line color for type of linear feature.
27. Use **small, closed shapes** to represent point entities (cities, etc). Use color, texture or boundary style to show attributes.
28. Use treemap if only **leaf nodes and a quantity** they are associated with matter
29. Node-link representation when **hierarchy and non-leaf nodes** matter and quantitative attributes are less important.
30. Animation? Motion between **0.5 to 4 degrees** of visual angle.

XII.7 Chapter 7

Visual objects and data objects

1. 3D size judgments? Use the **best possible set** of depth cues.
2. Minimize perceived distortions from off-axis 3D spaces, avoid **wide viewing angles**, horizontal viewing angle below 30 degrees.
3. 3D height field data? Use **draped grids** to enhance shape information. Best if data varies smoothly.
4. Use **cast shadows** to tie objects to a surface that defines depth. Surface should have strong depth cues (grid texture, etc) and be simple, objects should be close to it
5. 3D depth relationships? Use structure-from-motion by rotating the scene around point of interest.
6. Stereoscopic? Avoid placing objects **too close** to the screen where their edges are clipped.
7. 3D stereoscopic? Use highest possible horizontal resolution. Excellent **spatial and temporal antialiasing**
8. Adjust **virtual eye separation** to optimize perceived depth while minimizing diplopia.
9. 3D with strong and gridded ground plane? Use **drop lines** to add depth information for small numbers of discrete isolated objects.
10. 3D? Use **halos** to enhance occlusion if this is an important depth cue and overlapping objects have same color/luminance
11. 3D? Use the depth cues for the most **critical tasks**.
12. **3D node-link structures**? Use motion parallax, stereoscopic, halos
13. Textures to reveal surface shapes especially if in stereo. Only good for smooth surfaces, and texture is otherwise unused. Linear components, if one texture is on top of another, make it lacy and see-through
14. Rotating **surface and stereoscopic** viewing to enhance 3D shape.
15. **Bivariate scalar** field maps. Use shaded height field and color for the two. Shaded variable should be relatively smooth.
16. **Depth in 3D scatterplot**, rotate or oscillate a point cloud around a vertical axis. Use stereoscopic if possible.
17. 3D **cloud of points**, must judge morphology of boundary? Use cloud surface to shade points.
18. 3D trajectories = **shaded tube or box** with periodic bands for orientation cues. Motion parallax and stereoscopic if possible.
19. Stereoscopic viewing when **hand movements** are critical. Use proxy for hand if possible.
20. 3D environments with 1-to-1 mapping between hand and objects, ensure **relative positions** are correct. Minimize rotational mismatch (> 30 degrees).
21. Vertical polarity in 3D space = clear reference **ground** plane and gravity affected **familiar objects** on it
22. Vivid sense of **presence** in 3D = large FOV, smooth motion, lots of detail

XII.8 Chapter 8

Space perception and the display of data in space

1. Optimal identification = make important patterns, complex objects have a 4 to 6 degree angle. Only a gradual penalty if not so.
2. Use an object display if standardized sets of data must be analyzed repeatedly and data can be mapped to objects
3. Design object displays such that numbers are tied to recognizable objects representing components
4. Design layouts using connecting elements that clearly indicate physical connections between components
5. Design glyphs to have emergent properties revealing effect of important interactions between variables
6. Display glyphs should be more salient when critical values are reached
7. Represent components with geons (smooth and shaded spheres, cylinders, cones, boxes)
8. Use color/texture of geons to represent secondary objects
9. Fewer than 30 components, entities/relationships must be shown = use geon diagram
10. Represent relationship by joints, tubes. Small geon attached to bigger one to show component relationship.
11. Geon (easy to perceive, 3D) shapes to represent primary attribute of entities
12. 3D diagrams = lay as much as possible in 2D plane orthogonal to line of sight. Make sure all connections are visible.
13. 3D diagram = use transparent bag to express part-of relationships
14. Entities and links = size/thickness to represent strength.
15. Efficient and compact expression of human emotion, use emoticons
16. Visual image that represents a class of things = use canonical

example in its "normal" orientation but only if it exists.

17. Use icons for pedagogical purposes in infographics. Use only when no canonical or cultural image is available
18. Large number of data points = symbols instead of words/icons
19. Use words directly where the numbers of symbolic objects in each category is few and space is available
20. use Gestalt principles of proximity, connectedness and common region to link label and figure

XII.9 Chapter 9

Images, words and gestures

1. Use methods based on natural language (not visual patterns) to express detailed program logic
2. Graphical elements should be used to represent structure, like links.
3. Use methods based on natural language (not visual patterns) to represent abstract concepts
4. Complex information: separate components by their most efficient representations: words (spoken/written) or images (static/moving). Use the most cognitively efficient method for linking.
5. Exploratory text should be as close as possible and graphically linked
6. Presentations: speech should accompany graphics, not text
7. Use deixis (arrow) to link speech and graphics
8. Spoken words in visualization? Highlight components before speech.
9. Principles for assembly diagram: clear narrative sequence, components should be visible and identifiable, and spatial layout should be consistent from one frame to the next.
10. Use consistent representation from one part of a sequence to another. Similar views of 3D objects.
11. Use graphic devices to maintaint continuity from one view to another
12. Break down animated instructions into short meaningful segments. Allow users to play each separately.
13. Animation of human figures to show how to make specific movements

XII.10 Chapter 10

Interacting with visualizations

1. Fastest epistemic (knowledge or its validation) action: use hover queries. Only when query targets are dense and inadvertant queries aren't distracting.
2. Non-dominant hand should control frame-of-reference, dominant should make detailed selections
3. Moving objects on screen? Make sure the object moves in the same general direction as the hand
4. 3D navigation: sufficient number of objects must be visible to judge the relative view position.
5. Overview map to speed up acquisition of a mental map
6. Overview map to speed up large-scale navigation
7. Make each landmark visually distinct
8. Make landmarks recognizable as far as possible on all navigable scales
9. 3D map data: default controls should allow for tilt around horizontal and rotation around vertical, but not rotation around line of sight.
10. Overview map? Provide a "you are here" indicator
11. Navigation map should provide three views: north-up, track-up, track-up perspective (default)
12. Geometric fisheye distortion? allow maximum scale change of five
13. Geometric fisheye distortion? Meaningful patterns must always be recognizable.
14. Zooming interface? Default scaling rate: 3 to 4 per second. Allow this to be modified
15. Large 2D/3D data spaces? Consider providing one or more windows to show a magnified part of space. In overview provide markers for the magnified views.

XII.11 Chapter 11

Visual thinking process

1. Design cognitive systems to maximize cognitive productivity
2. Interactive node-link diagram? Provide pathfinding algorithm for complex paths
3. In large data spaces with small islands of critical information, enable different viewports to show magnified areas. Useful for tasks that require more than 3 visual working memory chunks.

These notes are incomplete. Read more by getting Colin Ware's "Information Visualization: Perception for Design". Images borrowed for educational fair use.