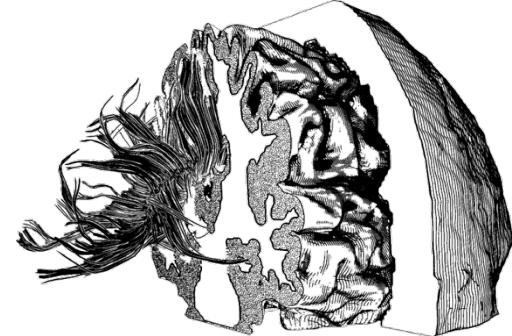
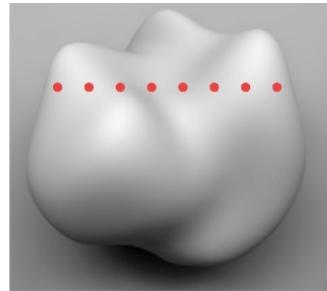
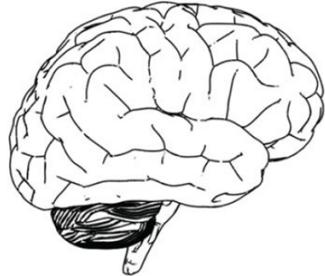
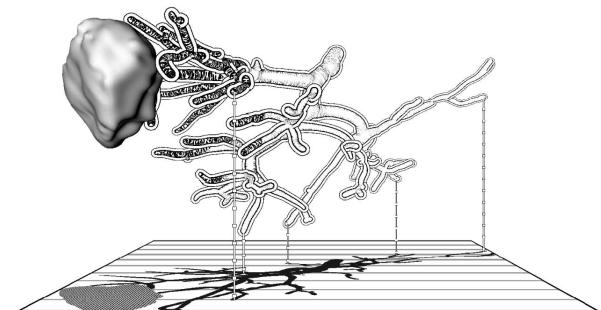
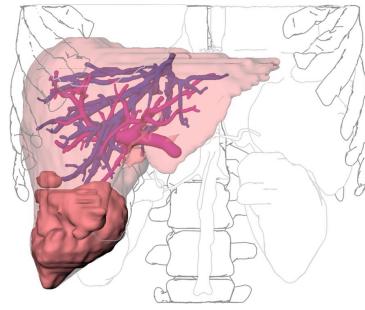
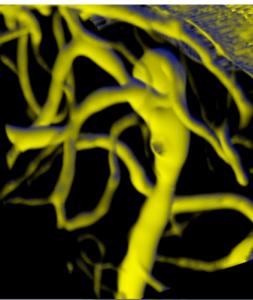


Perception-Guided 3D Medical Visualization



Learning Goals

Make you familiar with

- 3D visualization techniques that aim at improved shape and depth perception
- Evaluation strategies to assess the effects
- Selected evaluation results

There are many useful medical vis. techniques and their quality is not a matter of taste, but can be objectively assessed.

Outline

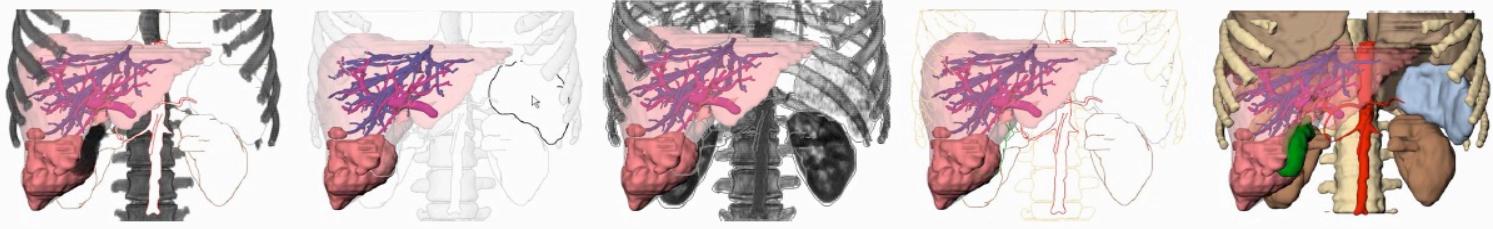
- Introduction
- Visual Perception
- Basic Techniques
 - Toon shading, chroma depth colors, distance color blending, halo effects
- Advanced Techniques
 - Illustrative visualization of anatomical shapes
 - Depth-enhanced vessel visualization
 - Advanced volume illumination
 - Fiber tract visualization

Introduction: Techniques

3D Medical Visualization comprises

- Surface Rendering (Isovalue, segmentation)
- Volume Rendering, incl. MIP, CVP, ...
- Line-Based Rendering
- Smart Visibility Rendering
- Hybrid combinations (Two Level Vol. Rendering, ...)
- Enhancements (Ambient occlusion, lighting effects, boundary emphasis)
- Parameters (transfer functions, transparency values, colors, textures, relevance thresholds)

Introduction



Series of images created by Tietjen et al. 2005 (subset from 33). Combinations of surface-, volume- and illustrative rendering lead to a huge design space. Not all variants be even considered and evaluated → Perceptual guidance needed.

Introduction: General MedVis. Tasks

Visualization of

- Patient anatomy, e.g. vasculature + tumor
- Layered anatomical structures, e.g. lung + bronchial tree
- Internal anatomy, e.g. colon, bronchial tree, vasculature
- Patient anatomy + simulation result, e.g. dose distribution, heat distribution
- Patient anatomy + planning information, e.g. implant, needles, access path, measurements, labels
- Intraop. data + planning information (Augmented Reality)

Introduction: Major Trends

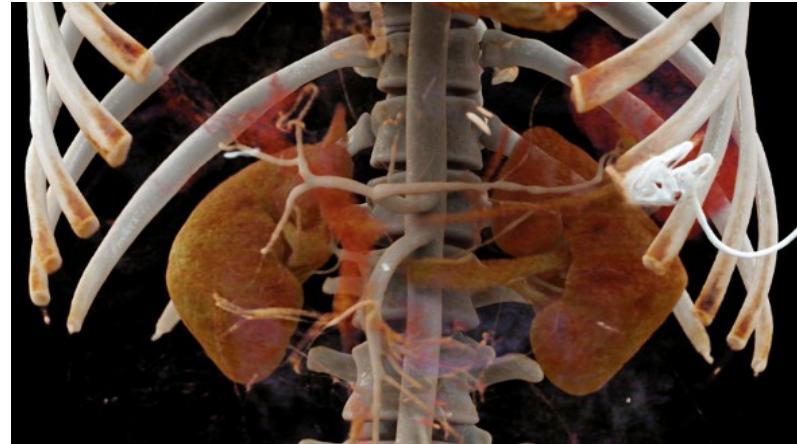
Major trends in perceptually motivated med. vis.:

- **Highly realistic** techniques, e.g. global illumination, realistic shadow, ambient occlusion and
- **Illustrative** techniques, e.g. illustrative shading, shadowing, hatching and feature lines.

Illustrative techniques, e.g. chroma depth shadows, inspired by artists' work.

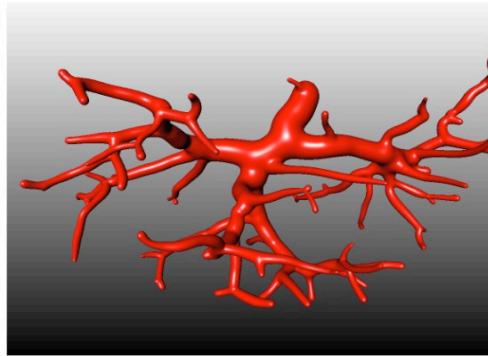
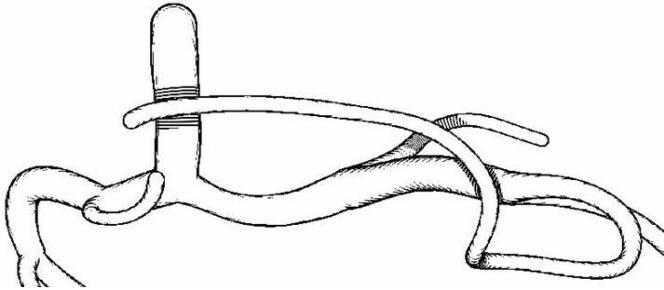
Example for high realism: „SIEMENS Cinematic Rendering“

Introduction: Major Trends



Cinematic rendering (© SIEMENS)

Introduction: Examples



Vessel visualization with depth cueing (Ritter, 2006), convolution surfaces (Oeltze, 2005)

Visualization Design

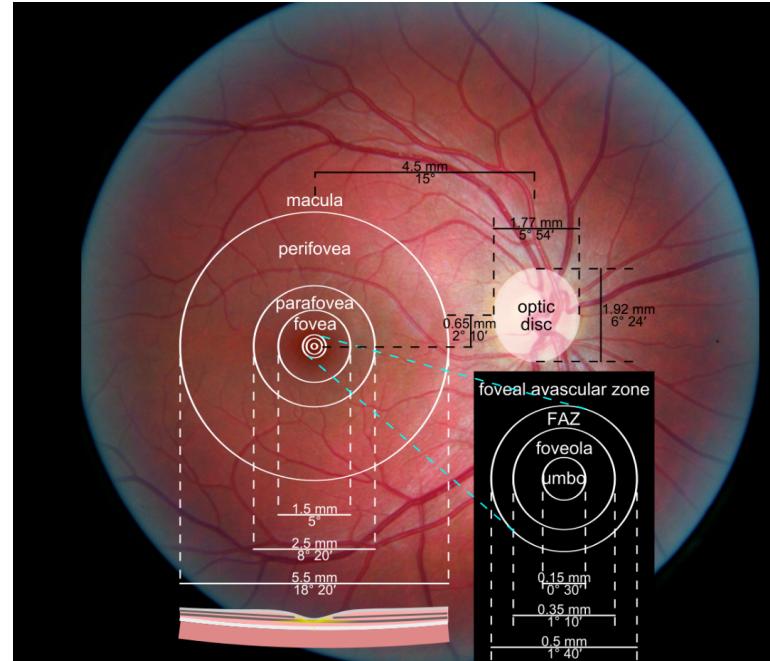
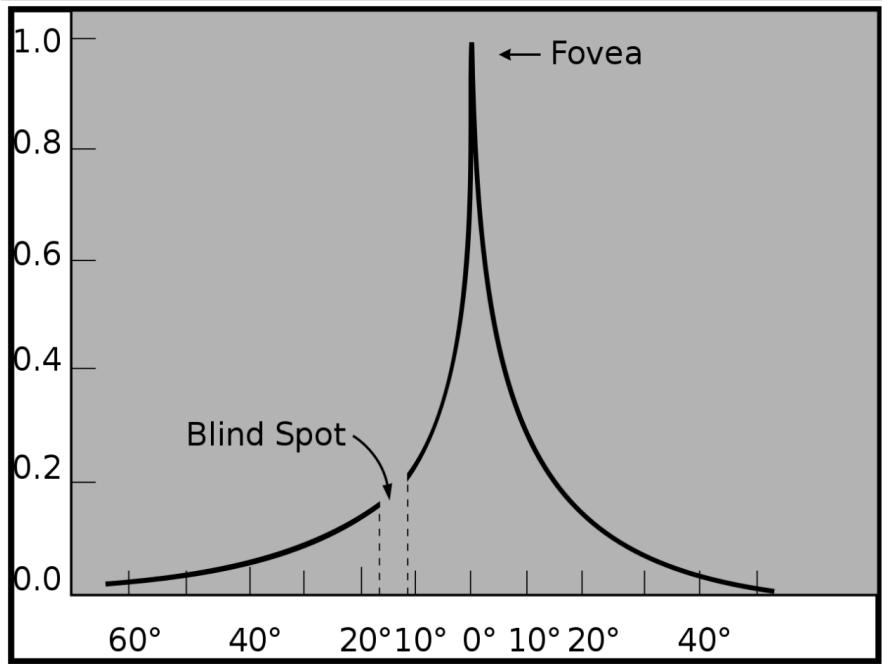
- **Requirements** stage: Observe and ask users, look at the software they are using, study their publications, identify conventions
- **Design and Implementation** stage: based on reqs., experience and intuition, prototype a solution (with a few variants), get feedback, select variant and fine tune
- **Emphasis**: Domain knowledge (often limited because only few users were observed) and visualization experience

Visualization Design

What is missing?

- A clear understanding of shape and depth perception
 - In particular for complex, undulated shapes with both convex and concave regions and for nested structures
- An evaluation/comparison w.r.t. shape categorization, shape orientation, depth judgement, depth assessment

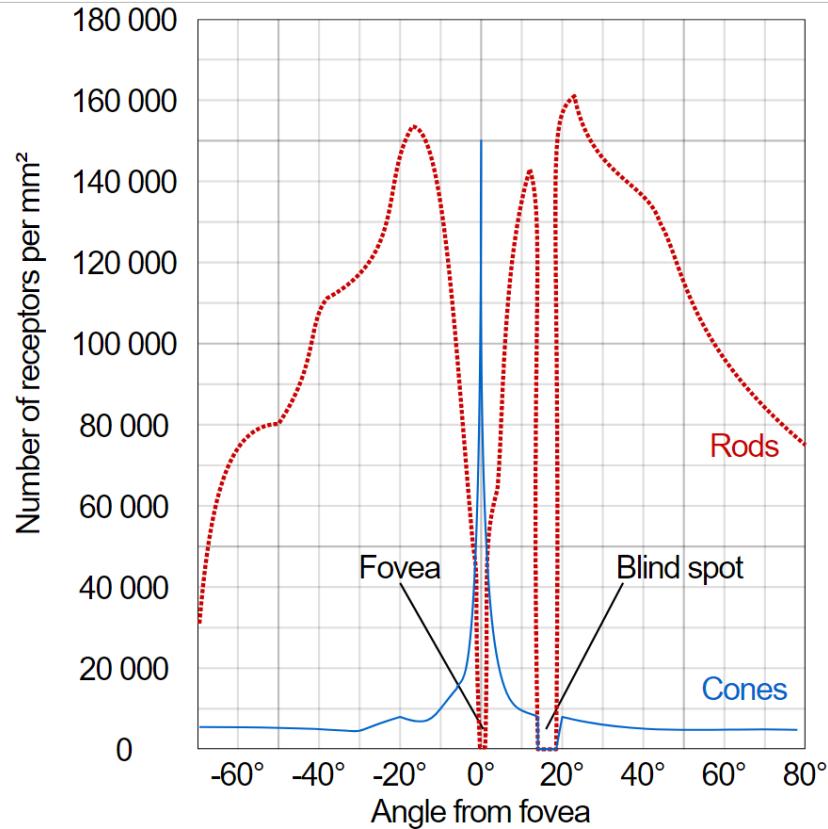
Visual Perception



Resolution of light-sensitive cells locally different.
→ Focus and context visualization, diff. LoDs

(From: Wikipedia)

Visual Perception



Two Types of light-sensitive cells:
Cones (for color vision) primarily
in the fovea; rods primarily in the
periphery

(From: Wikipedia)

→ Use saturated colors carefully, concentrate in a few regions

Visual Perception

Elaborate models for different aspects of perception

- Contrast perception
 - Relevant for viewing X-ray, CT/MRI data
- Color perception
- Motion perception (change blindness, change detection)
- Visual search theories
 - Relevant for emphasis techniques
- Flow perception (e.g. for optimizing weather displays)
- **Shape perception**
- **Depth perception**

Visual Perception: Shape Perception

Investigates whether participants can assess

- the *shape category* (convex, planar, concave) and
- the *shape orientation* (angle of the surface normal)

Depending on variables, such as surface texture, diffuse or specular illumination.

Basis: Gibson, 1950: *local texture gradients* as an essential source of information.

Texture gradient comprises local differences in scaling, density, and orientation of texture elements (texels).

Visual Perception: Shape Perception

Display of curved surfaces

- Does texture improve shape perception?
- Which types of texture are effective?

Tasks:

- Surface categorization via *forced choice* (convex, concave, saddle type, planar)
- Surface orientation with *gauge figures*
- Stimuli: complex double curved surfaces with planar areas, slightly and strongly bended regions

Shape Perception



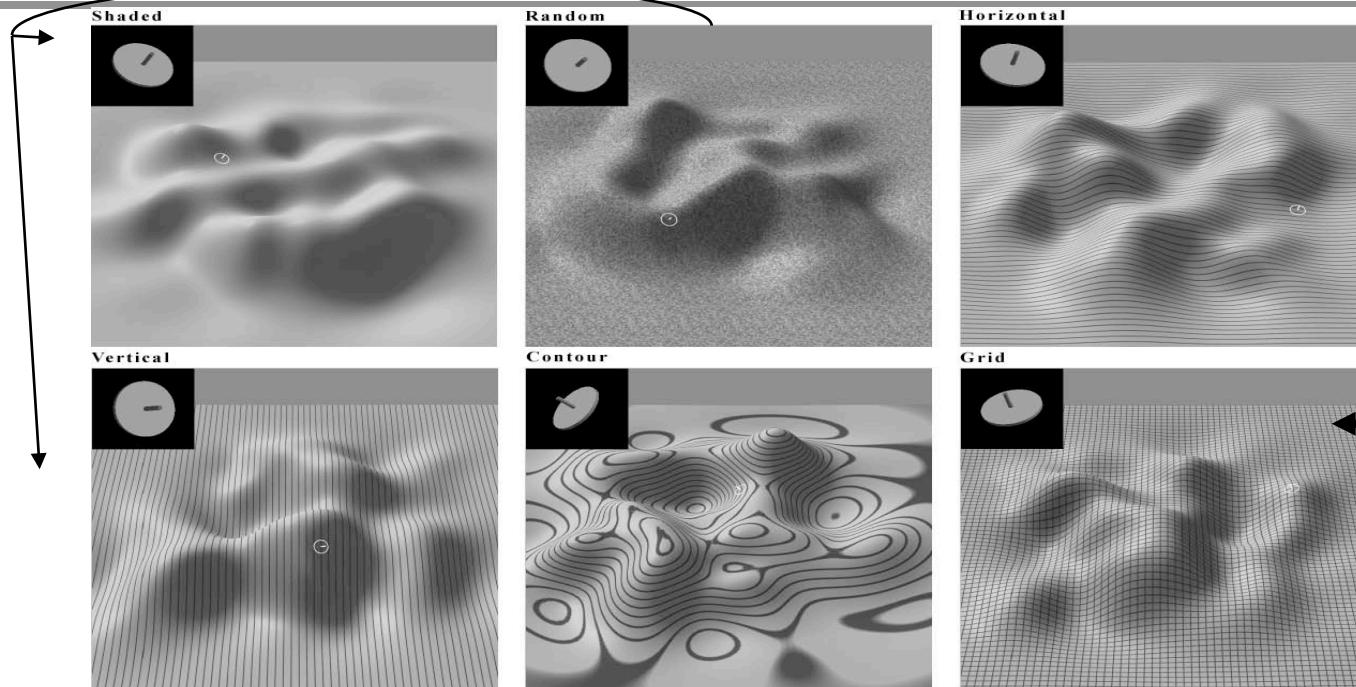
Baseline: Surface visualization with diffuse lighting (Phong Shading)

Right: with an additional texture that follows the surface orientation
(hatching lines represent principal curvature directions PCDs) (Kim, 2004).

Assumption that lines follow PCDs was stated early (Stevens, 1981) and often confirmed.

Shape Perception

Bad results
(mean error ~
20 deg.)



Clear
Winner
(mean
error; 12
degrees)

Textures employed by (Sweet, 2004). All surfaces shaded with diffuse and specular lighting from the same light source position.
Gauge figure shown enlarged (top left corner).

Shape Perception

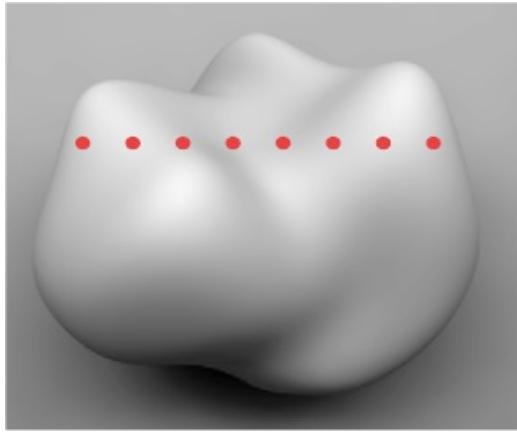
Consequences:

For the display of complex anatomical surfaces

- Shading essential (also in volume rendering)
- It can be added by
 1. A hatching texture consisting of (long) lines according to PCDs and orthogonal vectors or
 2. Feature lines (e.g. silhouettes and ridge-and-valley lines)

- (1) better for shapes with few landmarks, such as most organs.
- (2) better for shapes that benefit from „decomposition“, e.g. the brain, vascular pathologies.

Visual Perception: Experiments

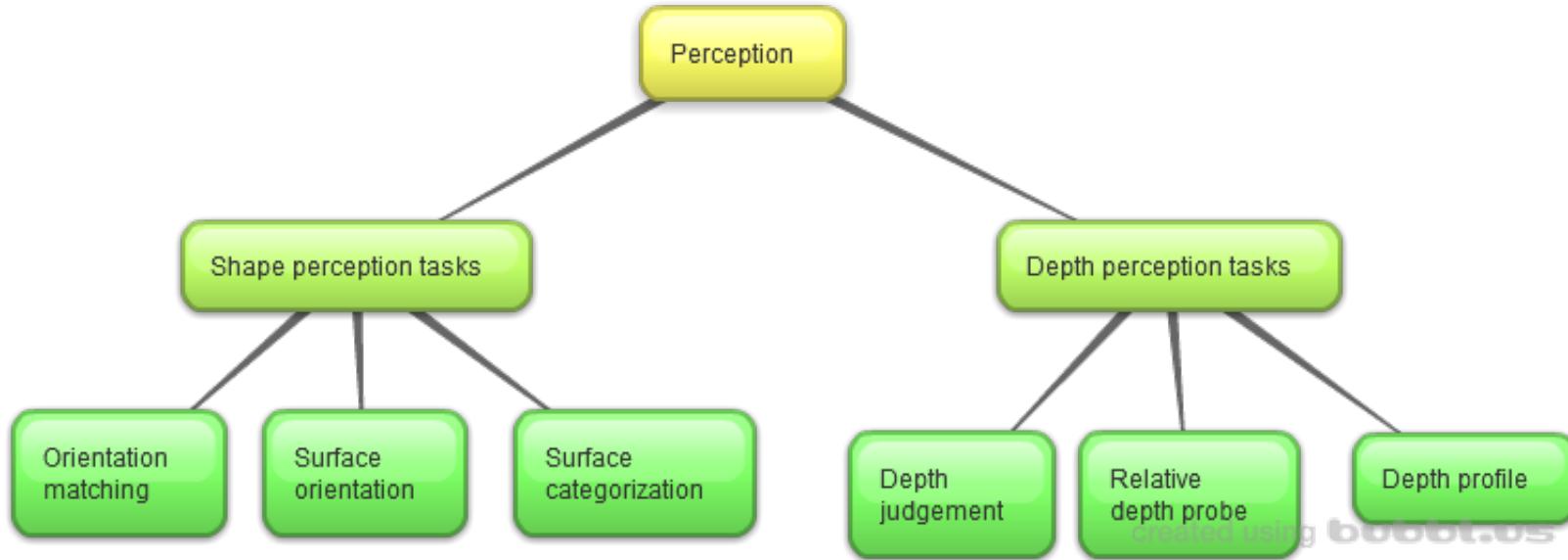


(From Todd et al., 2004).

Depth profile adjustment task: Set of horizontal points given.
Participants select minima and maxima and sketch the profile
along this line.

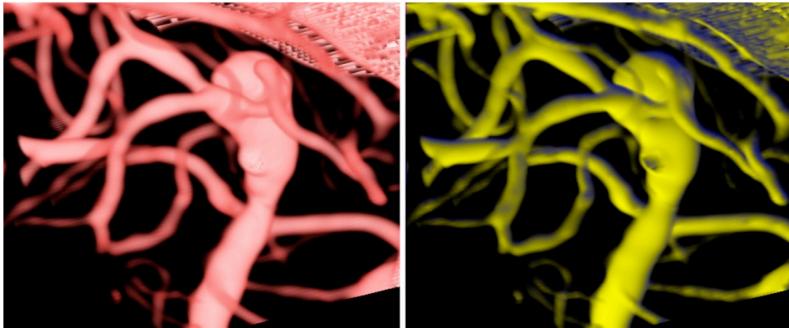
With shaded images, observers correctly assess minima and
maxima (93%) but underestimate the differences by a factor of 2.
(Todd, 2004)

Visual Perception: Tasks



Basic Techniques: Toon Shading

- Toon shading
 - (introduced by Gooch et al. 1998, inspired by artists)
 - Supports shape perception by applying a cool-to-warm color scale
 - $\text{Color} = K_{\text{cool}}(1.0 + L \cdot N)/2 + K_{\text{warm}}(1.0 - (1 + (L \cdot N))/2)$
 - N = normalized gradient at a voxel, L = lightvector

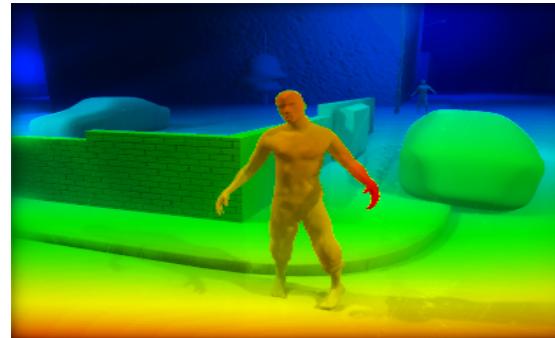


Normal shading
and toon shading
(Joshi et al., 2008)

Basic Techniques: Chroma Depth

Chroma depth shading

- Lens of the eye refracts colored light with different wavelength at different angles → effect employed for stereo perception
- Supports depth perception even without glasses (Steenblick, 1987)
- Depth value mapped to color (red is frontal, many hues, blue is distal)



[Source:](#)

Basic Techniques: Distance Color Blending

Distance color blending (Ebert/Rheingans, 2000):

- Dims volume color for farther away voxels
- Color in the frontal regions remains unchanged

$$\text{Color} = (1 - d) \cdot \text{Color}_{\text{original}} + d \cdot \text{Color}_{\text{background}}$$

- Traditional depth cueing combined with a color modulation
- Distant regions: color weighted with a background color
- Blue receptors (cones): long response time → focus on frontal regions is supported.
- Inspired by artists (aerial perspective)

Basic Techniques: Halos

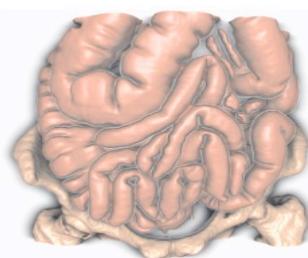
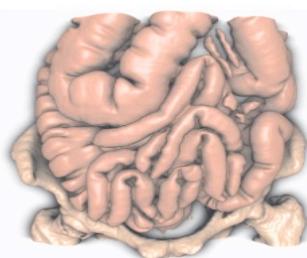
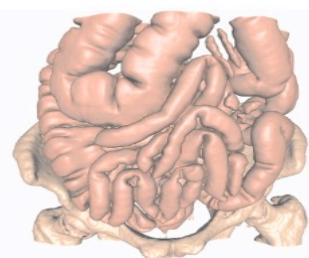
Halo effects (Ebert/Rheingans, 2000):

- emphasize foreground features with a surrounding „null halo“ → background object is de-emphasized
- computed per voxel by adding halo influences in the neighborhood

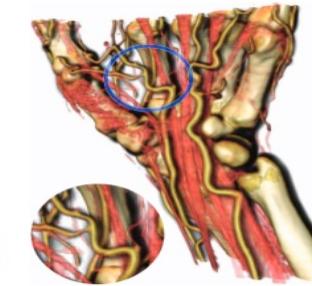
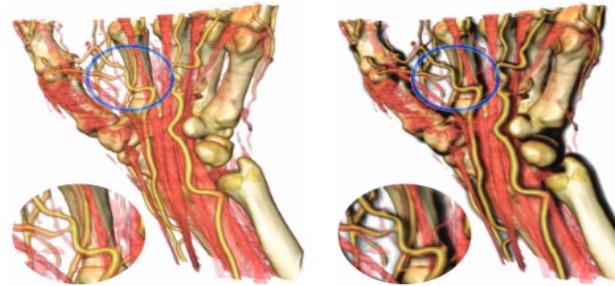
$$h_i = \left(\sum_n^{neighbors} \frac{h_n}{\|P_i - P_n\|^2} \right) (1 - \|\nabla_f(P_i)\|)$$

- Halo influence inversely proportional to the distance and to the gradient magnitude

Basic Techniques: Halos

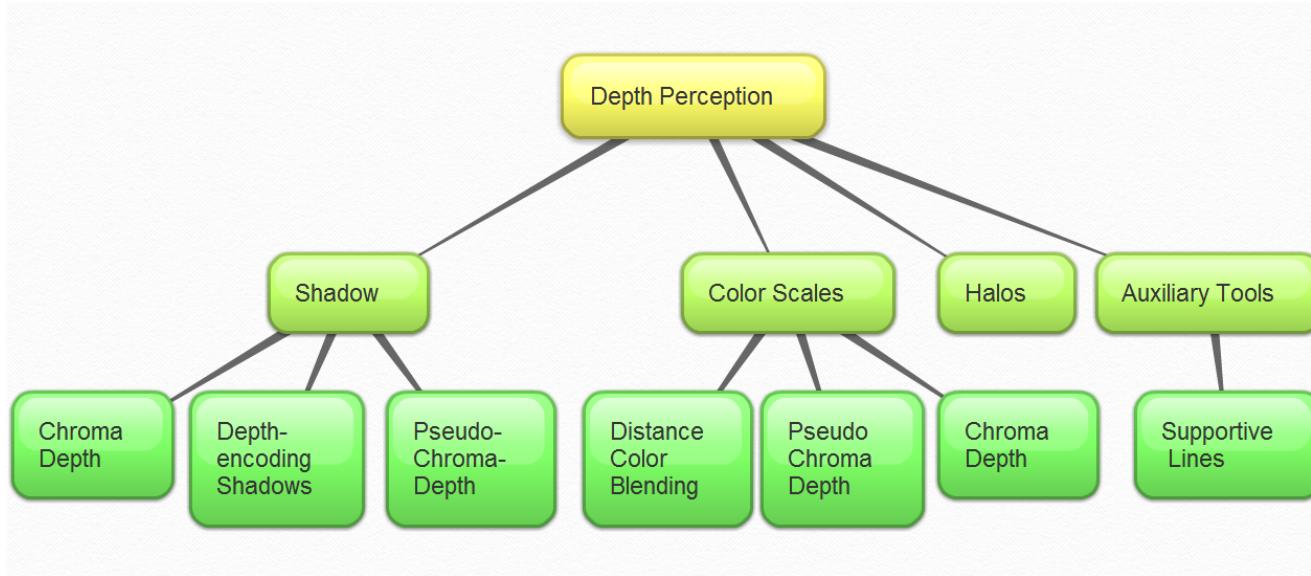


Volume rendering of a colon. Middle: enhanced with a smooth shadow-like halo, right: further enhanced with a bright semi-transparent halo (Bruckner, 2007)

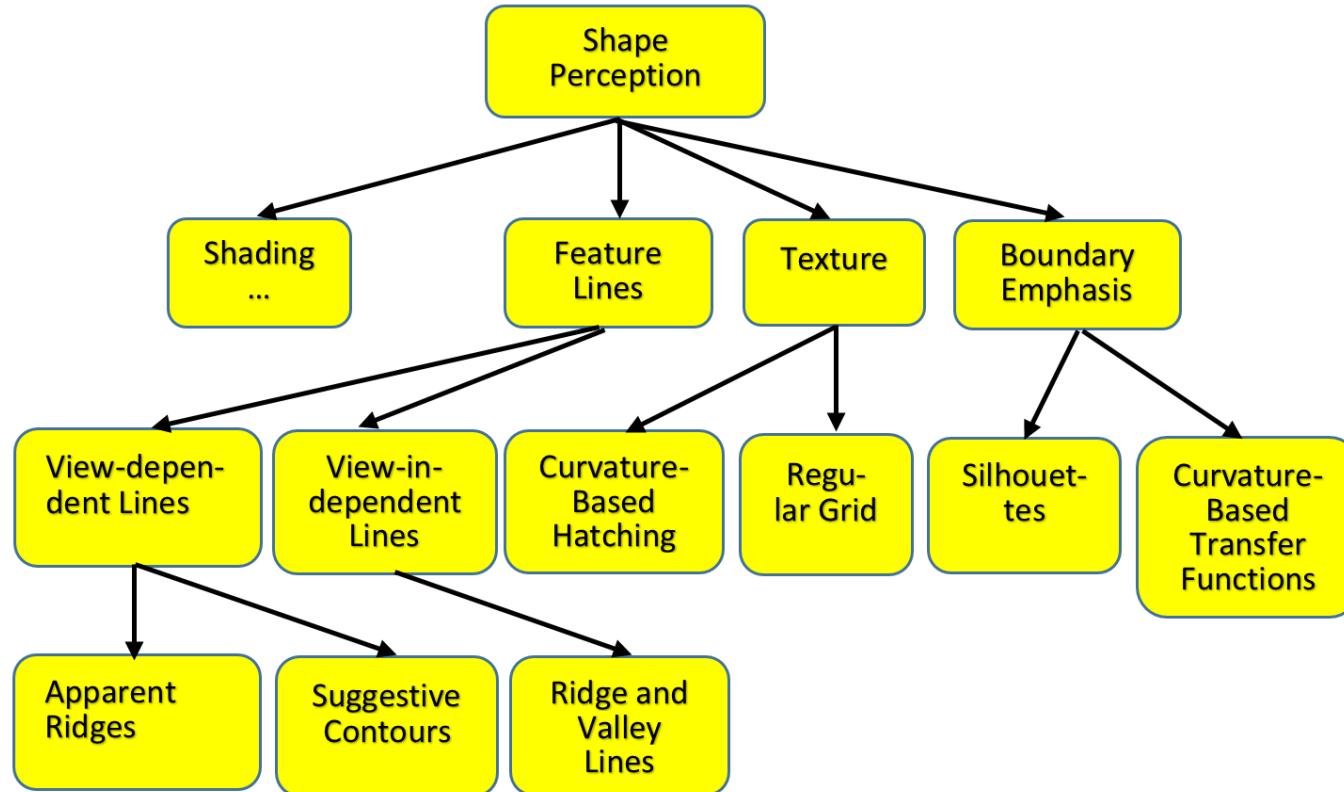


Volume rendering of segmented CT data. Right: enhanced with an emissive halo (darkening around foreground vessels) (Bruckner, 2007)

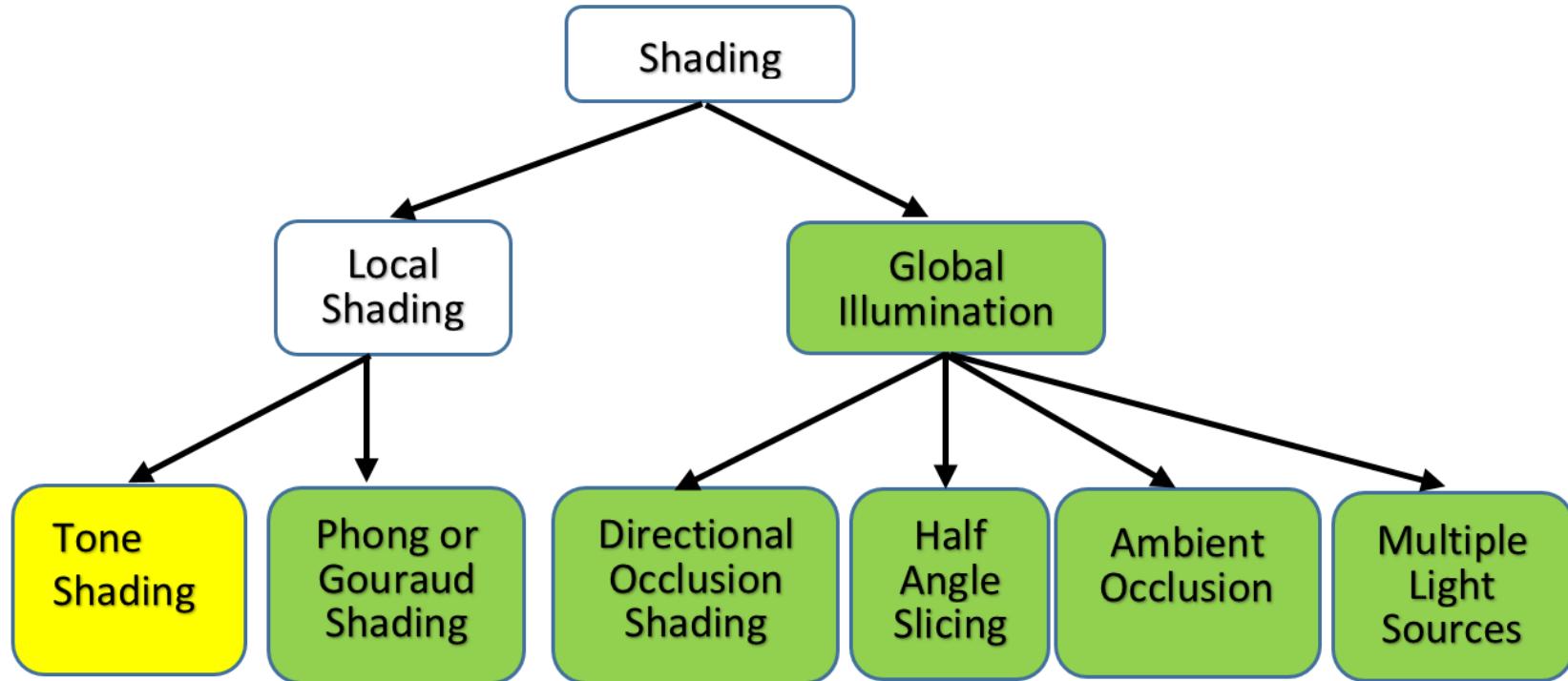
Depth Perception Techniques



Shape Perception Techniques



Shape Perception Techniques



Advanced Perception-Based Techniques

- Illustrative visualization of general anatomical shapes
 - Enhanced Two-Level Volume Rendering
- Depth-enhanced vessel visualization
 - Basic Techniques
 - Illustrative Techniques
- Advanced Illumination
 - Highly realistic rendering
 - Combination of different light sources
 - Chroma Depth Shadows
- DTI visualization

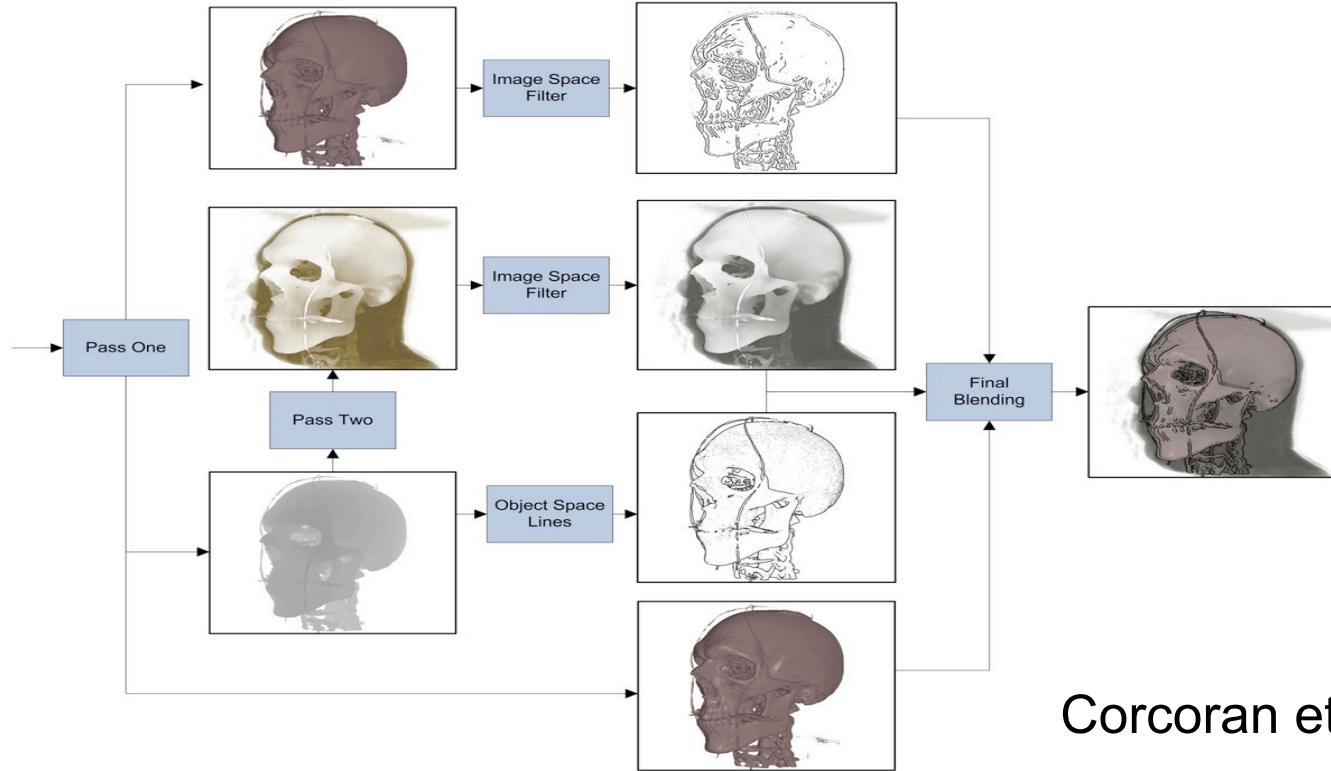
Illustrative Visualization of Anatomical Shapes

Volume rendering may be complemented by adding

- Image-space edges (Sobel, Canny-Edge, ...) realized as GPU shaders
- Object space lines (Silhouettes, Suggestive Contours, ...)

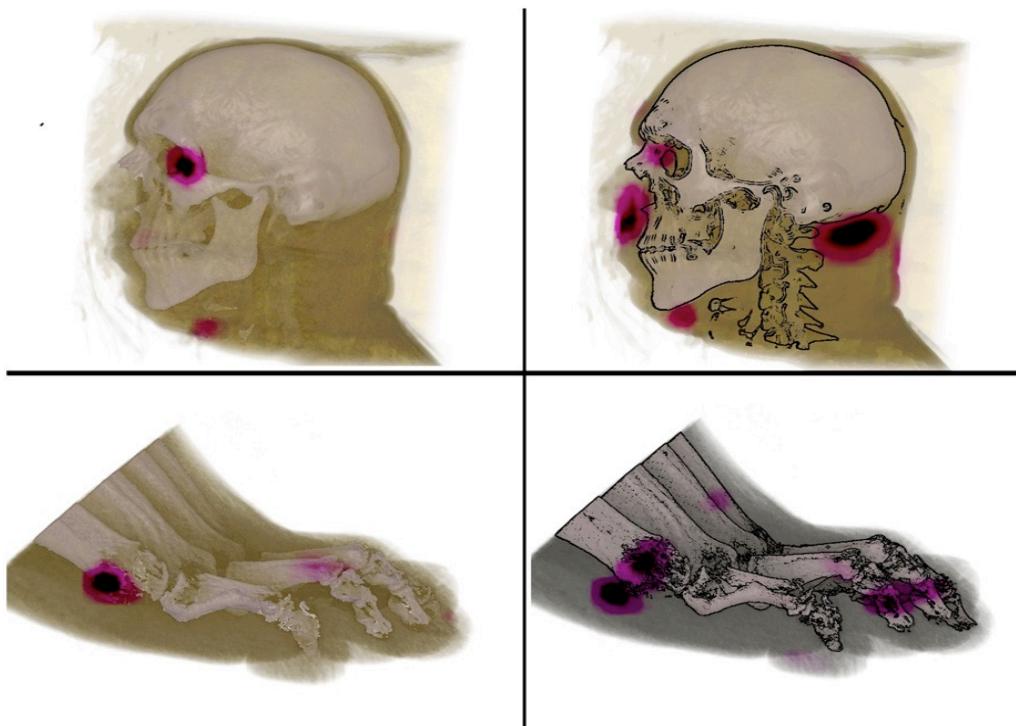
Corcoran et al. „Perceptual enhancement of two-level volume rendering”, 2010

Illustrative Visualization of Anatomical Shapes



Corcoran et al., 2010

Illustrative Visualization of Anatomical Shapes

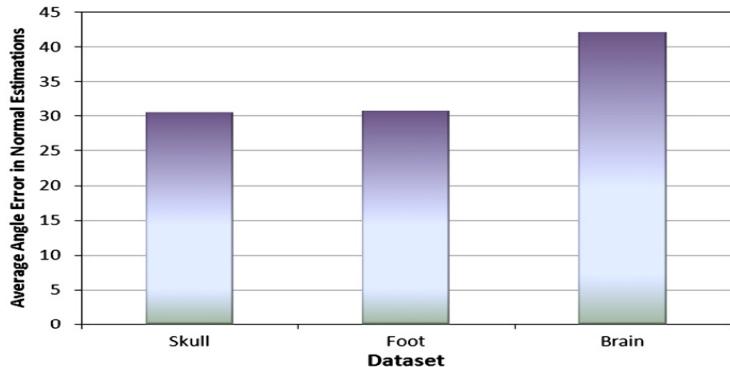


Left images: normal rendering,
top right: Sobel filter,
bottom right: suggestive contours + saturation variation (From: Corcoran et al., 2010)

Illustrative Visualization of Anatomical Shapes

Shape orientation task with gauge figures for three anatomical models with 14 „naive“ users.

The unfamiliar brain model leads to the highest angular deviation.



From: Corcoran et al., 2010

Illustrative Visualization of Anatomical Shapes

Selected results (brain model, gauge figure task):

Average normal error

Without stylization: 53 deg.

Sobel edge: 33 deg.

Canny edge: 36 deg.

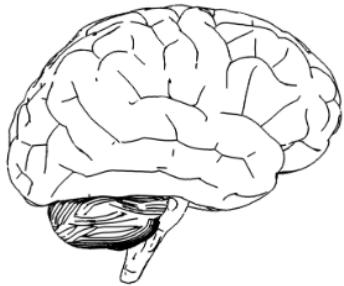
Silhouettes: 40 deg.

Sugg. Contours (SC): 38 deg.

Sobel/SC: 48 deg.

Canny/SC: 45 deg.

Illustrative Visualization of Anatomical Shapes



Left: crease lines and contours

Middle: ridges+valleys and contours

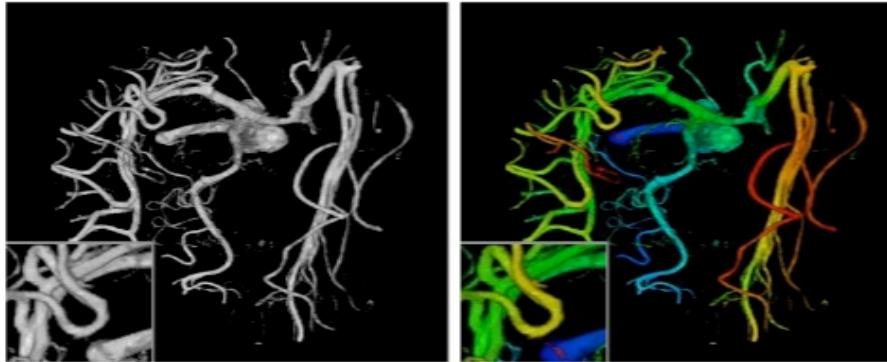
Right: Suggestive contours (Lawonn/Preim, 2015)

In particular, the display of contours and curvature extrema is perceptually well motivated.

Depth-Enhanced Vessel Visualization

Motivation: Static images (documentation, publication) are difficult to interpret.

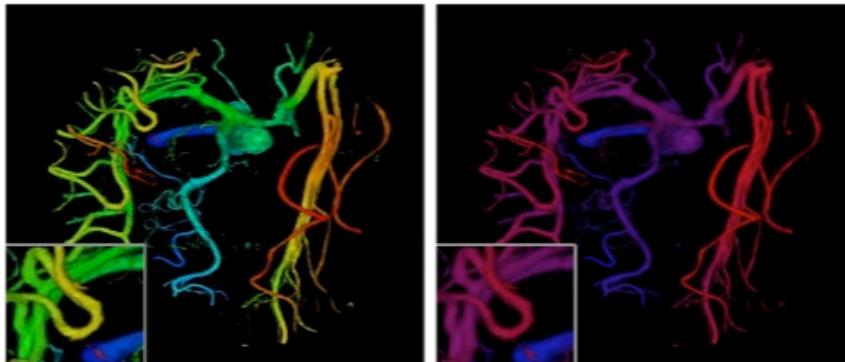
Improved angiography visualization with chroma depth shading (Ropinski, 2006)



Normal shading and
chromadepth shading
(Ropinski et al., 2006)

Depth-Enhanced Vessel Visualization

- Chromadepth scale has many hues and is distracting when the geometry is complex.
- Pseudochromadepth (Ropinski et al., 2006) incorporates two hues only: Red for foreground and blue for background
- Difference to distance color blending: no object foreground color considered



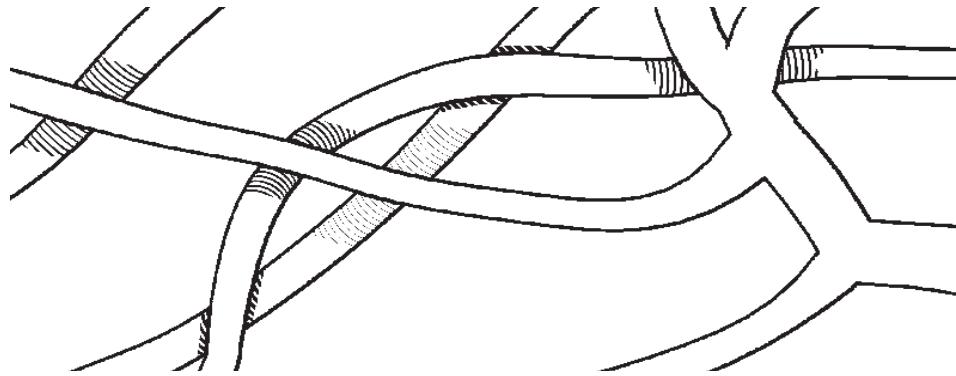
Chromadepth shading and
Pseudochroma shading
(Ropinski et al., 2006)

Depth-Enhanced Vessel Visualization

Evaluation with 14 participants (Ropinski et al., 2006):

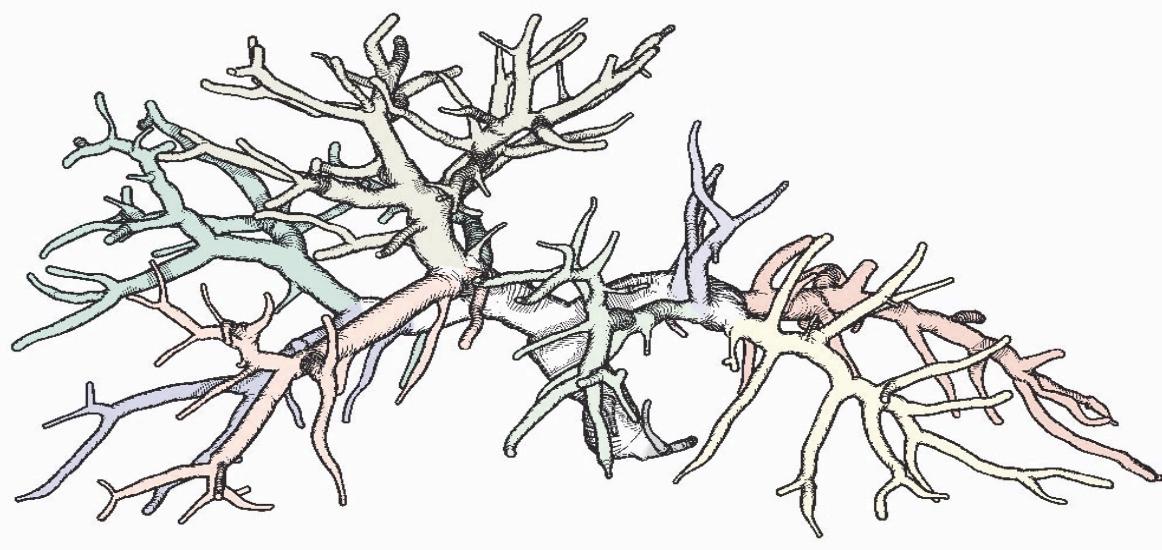
- Task: Depth judgement tasks, pairs of markers
- Independent variables: color scale, edge enhancement
- Dependent variables: error, task completion time
- Major results (Avg. Error):
 - standard shading: 26%
 - Chromadepth: 21% (preferred by 4 users)
 - Pseudochromadepth: 7% (preferred by 4 users)
 - Blended edges: 10%
- Task completion time very similar

Depth-Enhanced Vessel Visualization

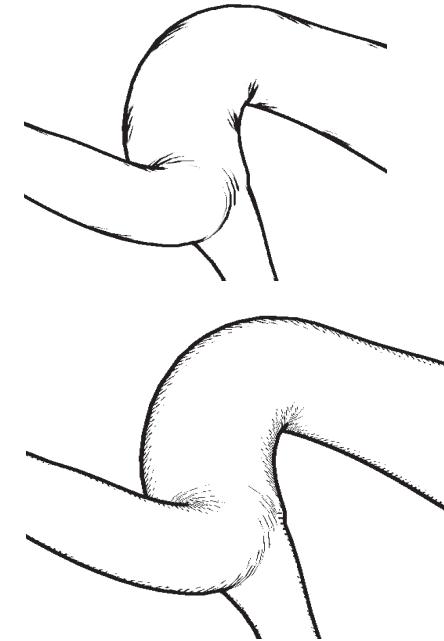


Occlusions (most important depth cue!) emphasized.
Density of the hatching texture indicates distance to the
foreground vessel at junctions. Distance-encoded shadow
(Ritter et al., 2006)

Depth-Enhanced Vessel Visualization



Stroke frequency modulated according to depth differences (Ritter et al., 2006)



Depth-Enhanced Vessel Visualization

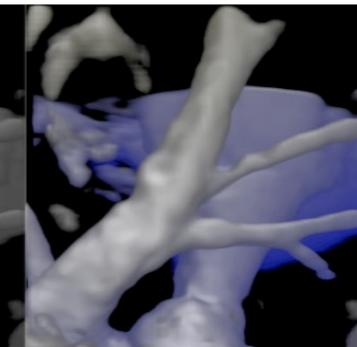
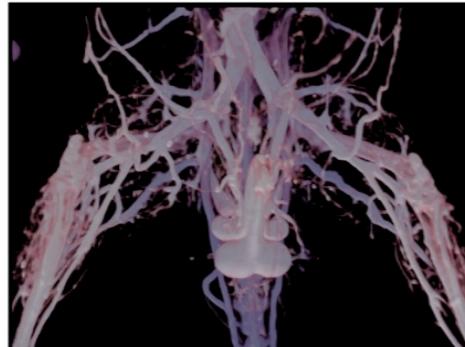
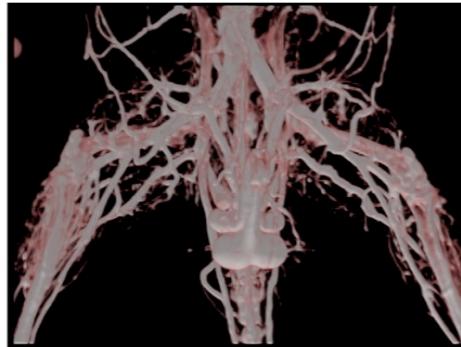
Illustrative vessel visualization, Ritter et al., 2006

- web-based questionnaire (no controlled environment)
- 160 subjects (77 females, 38 physicians, students of medicine)
- Depth judgement task, sort 3 points according to depth with a conventional visualization and stroke hatching (identical camera and lighting; no interaction enabled)
- Strongly improved depth perception over Gouraud shading could be shown

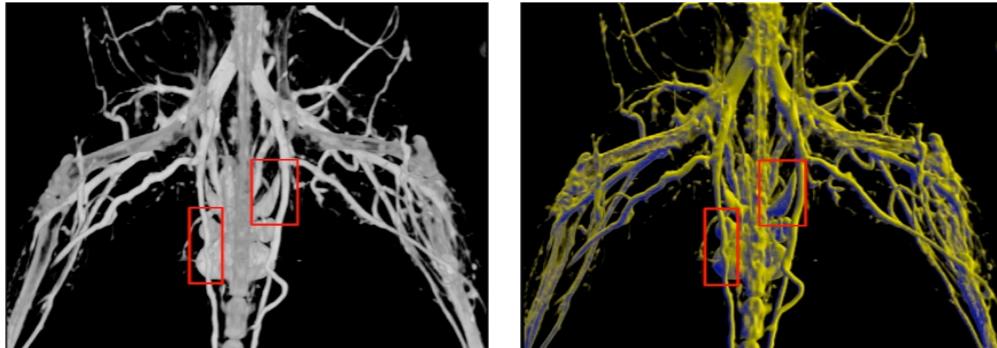
Depth-Enhanced Vessel Visualization

Comprehensive shape and depth cues

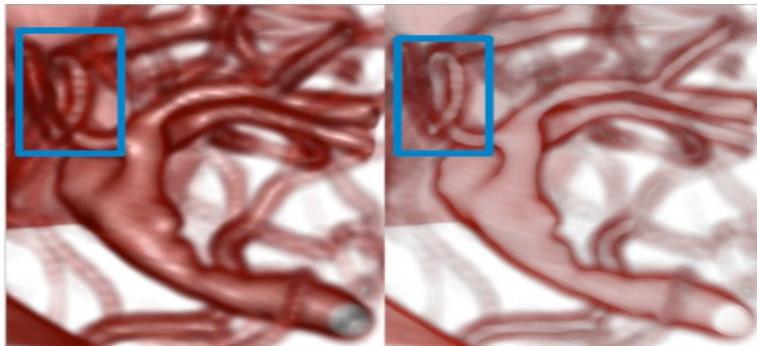
- Based on advanced vesselness filter (considers tubular structures)
- Distance color coding
- Toon shading
- Halos



Depth-Enhanced Vessel Visualization

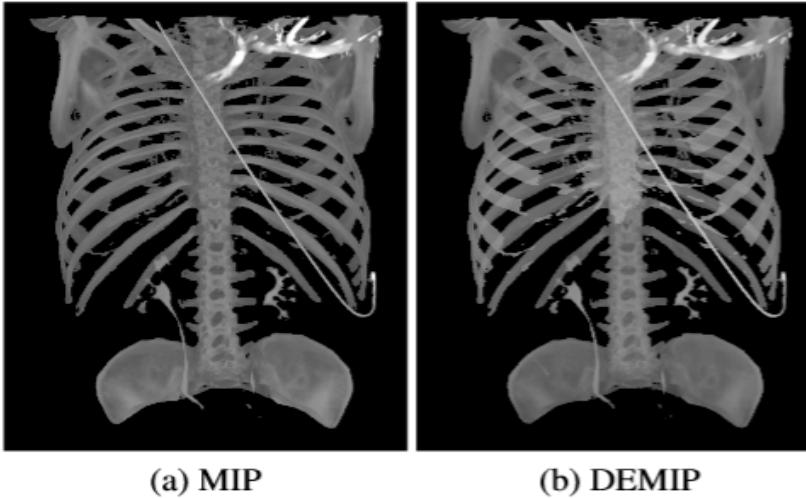


Normal shading vs. Toon shading (Joshi, 2008)



Vessel visualization without and with halos (Joshi, 2008)

Depth-Enhanced MIP

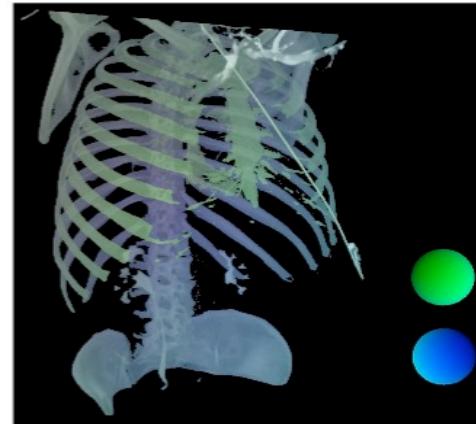
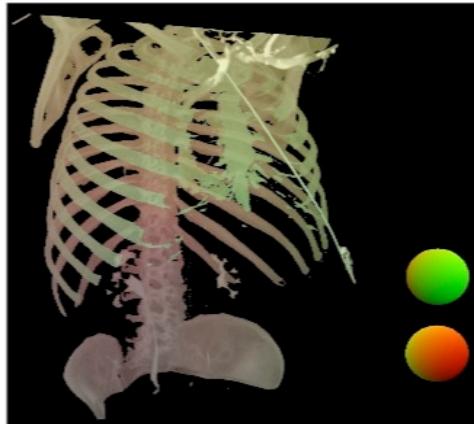
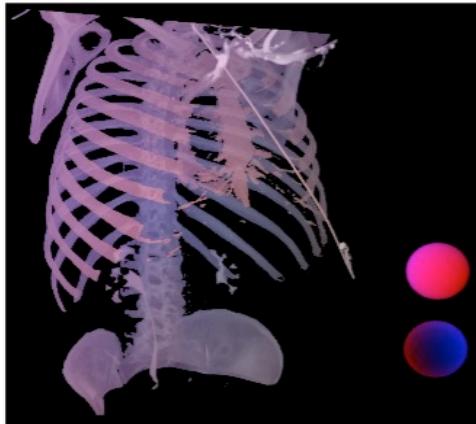


Depth impression by MIP strongly limited. Depth enhancement: mapping depth values to gray values.

Depth weighting as adjustable parameter
Vazquez, 2010).

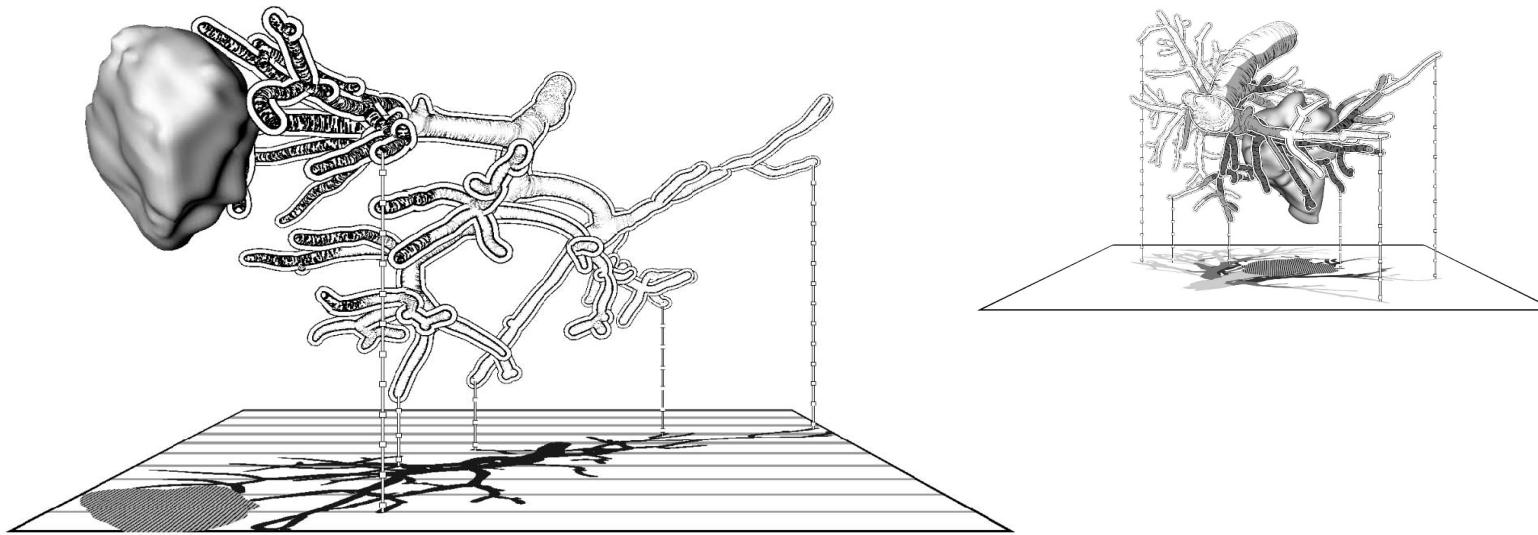
(From: Diaz/

Depth-Enhanced MIP



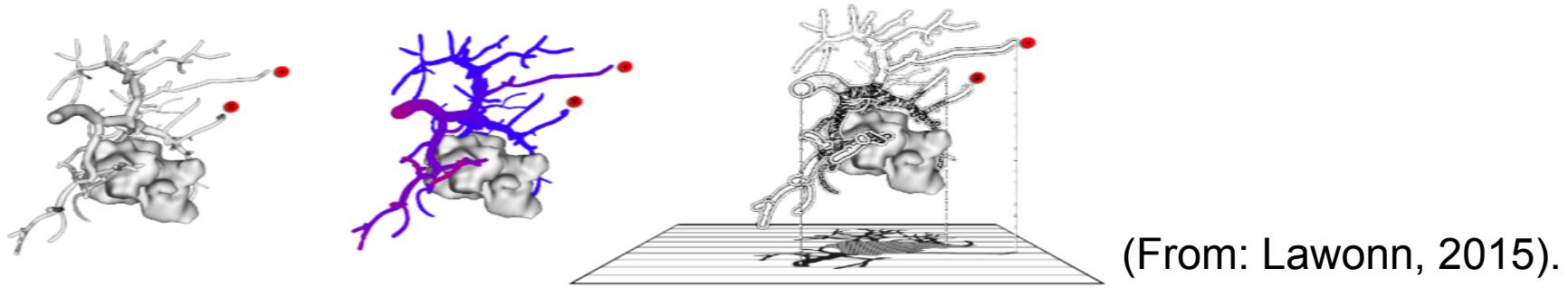
Further enhancement: color-coding depth. Effect of different color scales. Left scale resembles Ropinski's Pseudochromadepth (Diaz/Vazquez, 2010)

Depth-Enhanced Vessel Visualization



Illustrative visualization of vascular structures combined with shadows and supportive lines – a games-inspired vis. technique (Lawonn, 2015).
Texture indicates distance to the tumor (safety margin)

Depth-Enhanced Vessel Visualization



(From: Lawonn, 2015).

Stimuli: Phong Shading, Pseudo Chroma Depth Shading, DE Vessel Vis
(illustrative rendering + shadows + supporting lines)

Tasks: Depth judgement tasks

Users: 50 (8 physicians, 19 females)

With Phong shading, only 48 % answers were correct. With Chroma Depth Shading and DE Vessel Vis: 80%

Task completion times: 10.9 s (PS) 13.1 s (CDS), 14.1 s (DE Vessel Vis)

Advanced Illumination

Position and intensity of light sources have a strong effect on detail recognition.

- For optimal shape perception combine
 - Key lights (highest intensity, top left from the shape)
 - Fill lights (secondary light, frontal, right)
 - Back lights (enhances silhouette)
- Local illumination models show excessive surface details
Global illumination adds shadow and more faithful representation of reflection.

(Perceptual theory: Berbaum, 1983; Ramachandran, 1988)

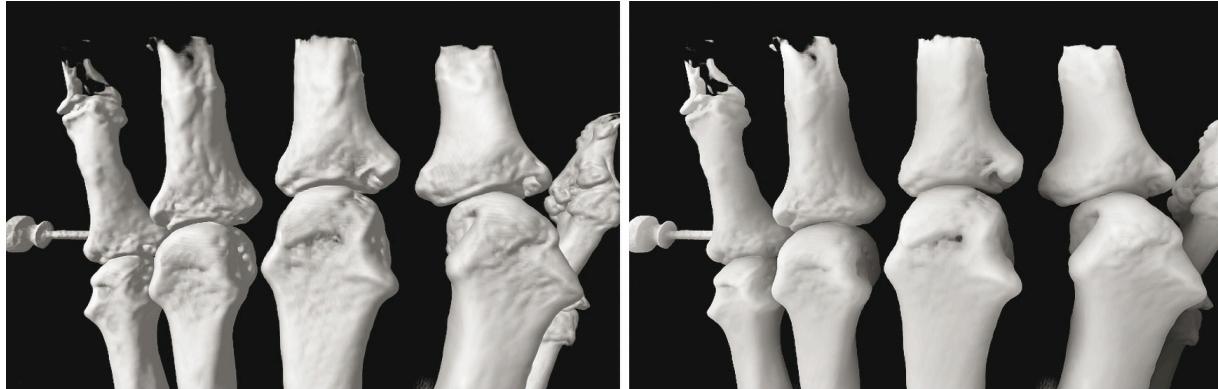
Advanced Illumination



Different lighting configurations: Left keylight only, middle: keylight + fill light, right: additional backlight (blue).

Visualization and diagnostic task: detect erosions from rheumatoid arthritis (Zheng, 2014)

Advanced Illumination



Local illumination: more details (left), global illumination: easier to interpret (softer boundaries).

User study: number of diagnostic errors (detection of bone erosions) reduced significantly AND users were twice as fast (Zheng, 2014)

Consequence: Both images should be presented and explored.

Advanced Illumination

How to evaluate perceptual effects of lighting?

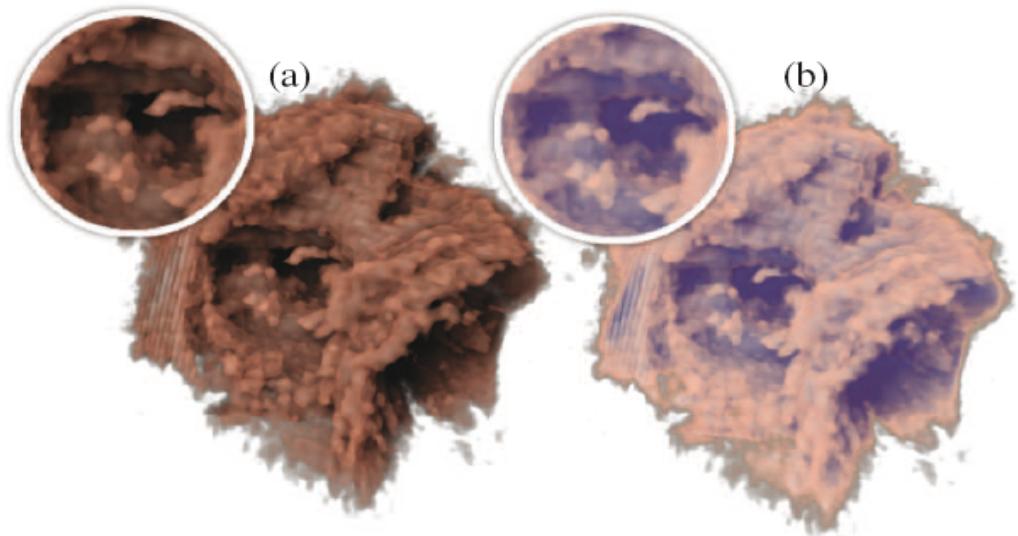
In addition to shape orientation and categorization tasks, specific metrics were developed (Zhang, 2013 and Shacked, 2001).

Components:

- Deviation of the resulting histogram from a perfectly equalized histogram
- Variance of the luminance values
- Detected edges prominence

Advanced Illumination

Realistic shadow representation: low contrast in shadowed region.
To improve detail recognition, shadowiness mapped to bluish colors.



Chroma Depth Shadows (Solteszova et al., 2010)

Advanced Illumination

Choice of the color scale:

- A line within the CIELAB color space, a perceptually linearized color scale (Euclidean distances in that color space correspond to perceived distances of color)
- Idea of illustrative shading with a cool-to-warm color scale goes back to Gooch (1998)

Advanced Illumination

Shape perception: gauge figure task

- Stimuli: 1005 images with 5 shadow colors
- User group: 8 physicians, no females
- Lowest angular deviation achieved with the brightest shadow color

Depth perception: depth judgement tasks

- Stimuli: 506 cardiac ultrasound data, presented with Phong shading, conventional (soft) shadows, and chroma-depth shadows.
- User group: 63 users (8 physicians)
- Tendency (not significant) for best results with chroma depth shadows

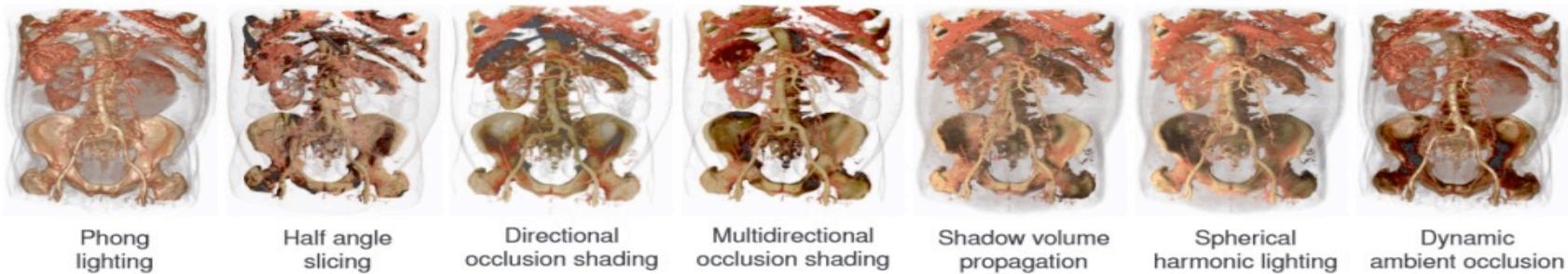
Advanced Illumination: Variants

- Baseline: Phong shading, using gradients as normals
- Half-angle slicing, global illumination method
 - two pass approach,
 - No constraints w.r.t. light source position
 - Creates hard shadows (Kniss et al., 2003).
- Directional occlusion shading
 - Similar to ambient occlusion (visibility-based shading)
 - Creates soft shadows (Schott et al., 2009)
- Multidirectional occlusion shading
 - More flexible lighting (Soltészová et al., 2010)

Advanced Illumination

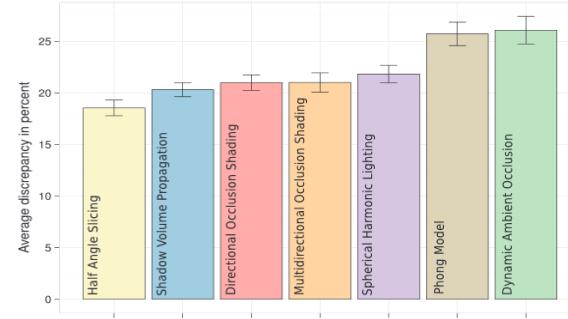
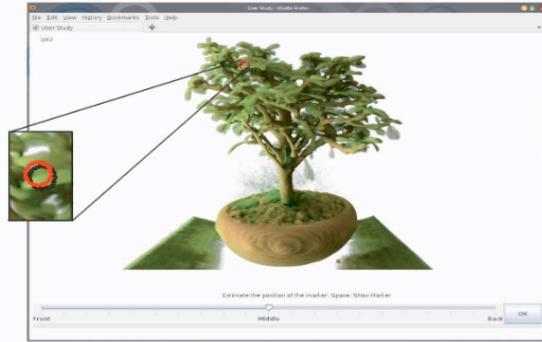
Investigation of depth perception in a monoscopic setting
(Lindemann, 2011):

- Comparison of 7 illumination techniques (incl. the 4)



- Depth judgement task (pairs of markers were presented)
- Absolute depth assessment task

Advanced Illumination



Users assessed depth in relation to the extent (0,1).

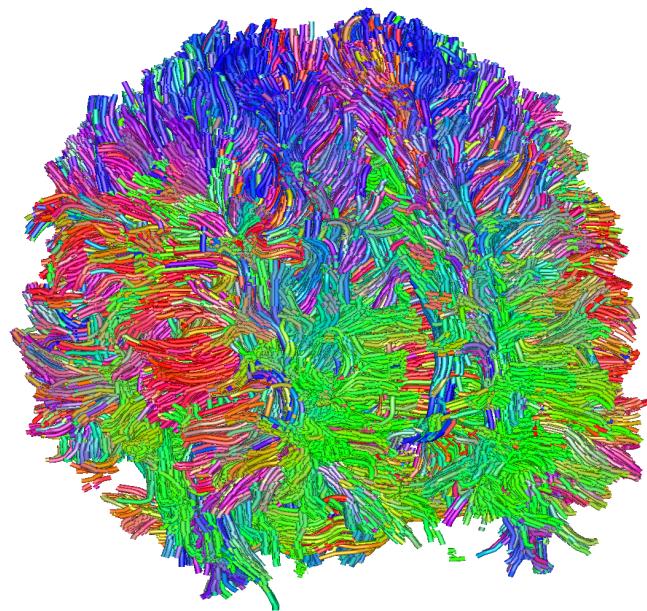
The Phong model and dynamic ambient occlusion were significantly worse compared to other techniques.

No significant differences in the task completion time.

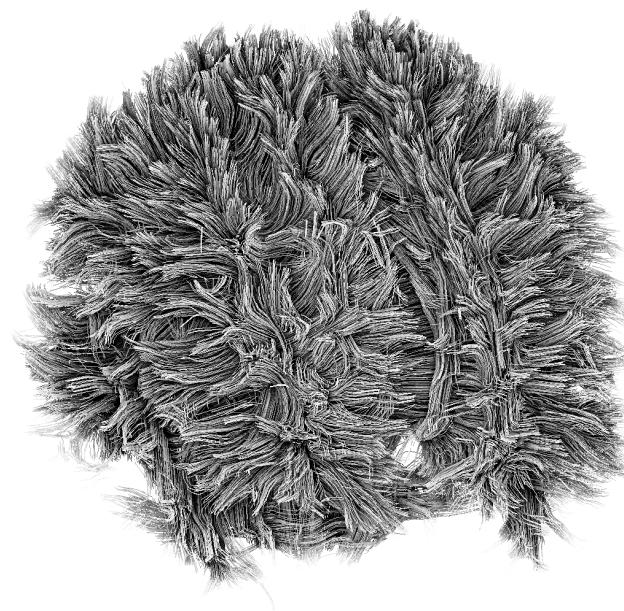
→ Advanced volume illumination improves depth perception.

Fiber Tract Visualization: General Approaches

tube-based primitives + illumination

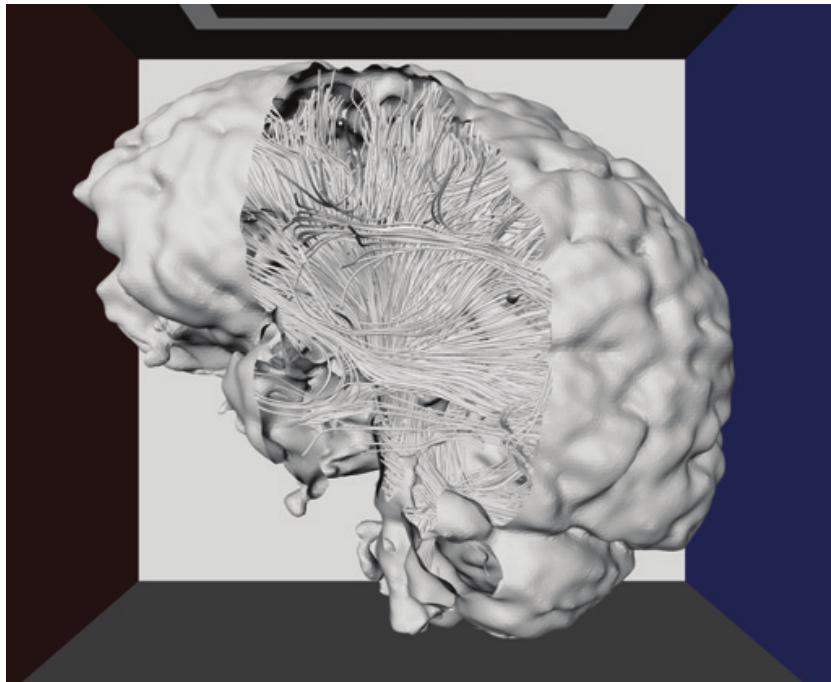


line-based primitives

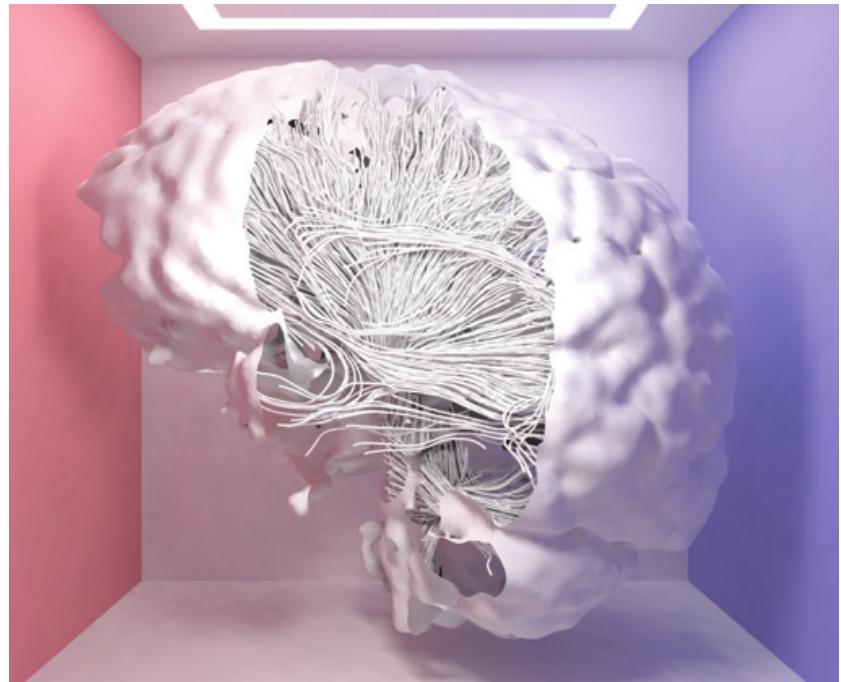


Fiber Tracts: Tube-based Visualizations

local illumination

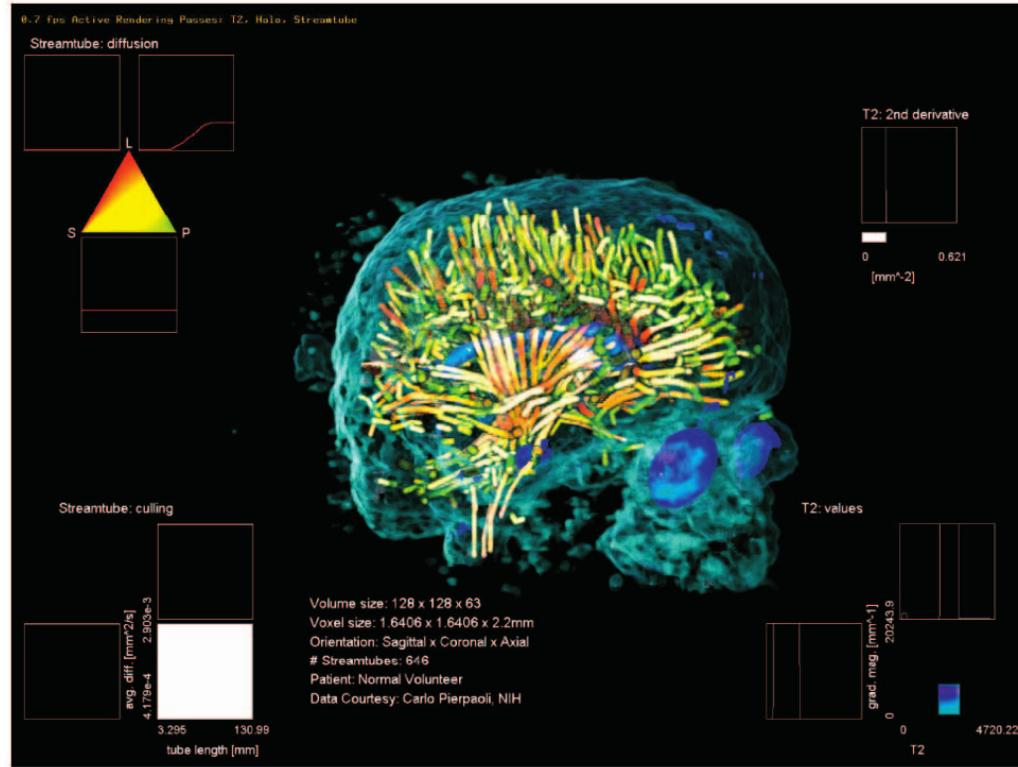
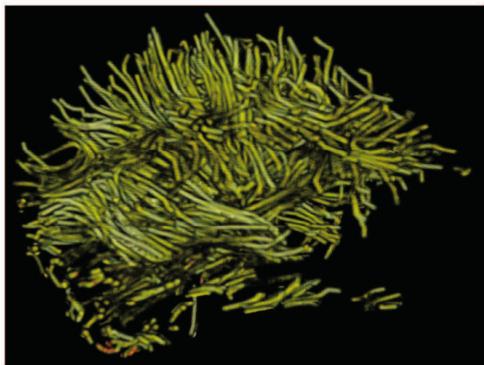
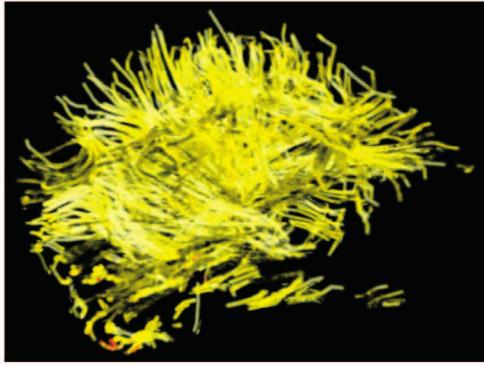


global illumination



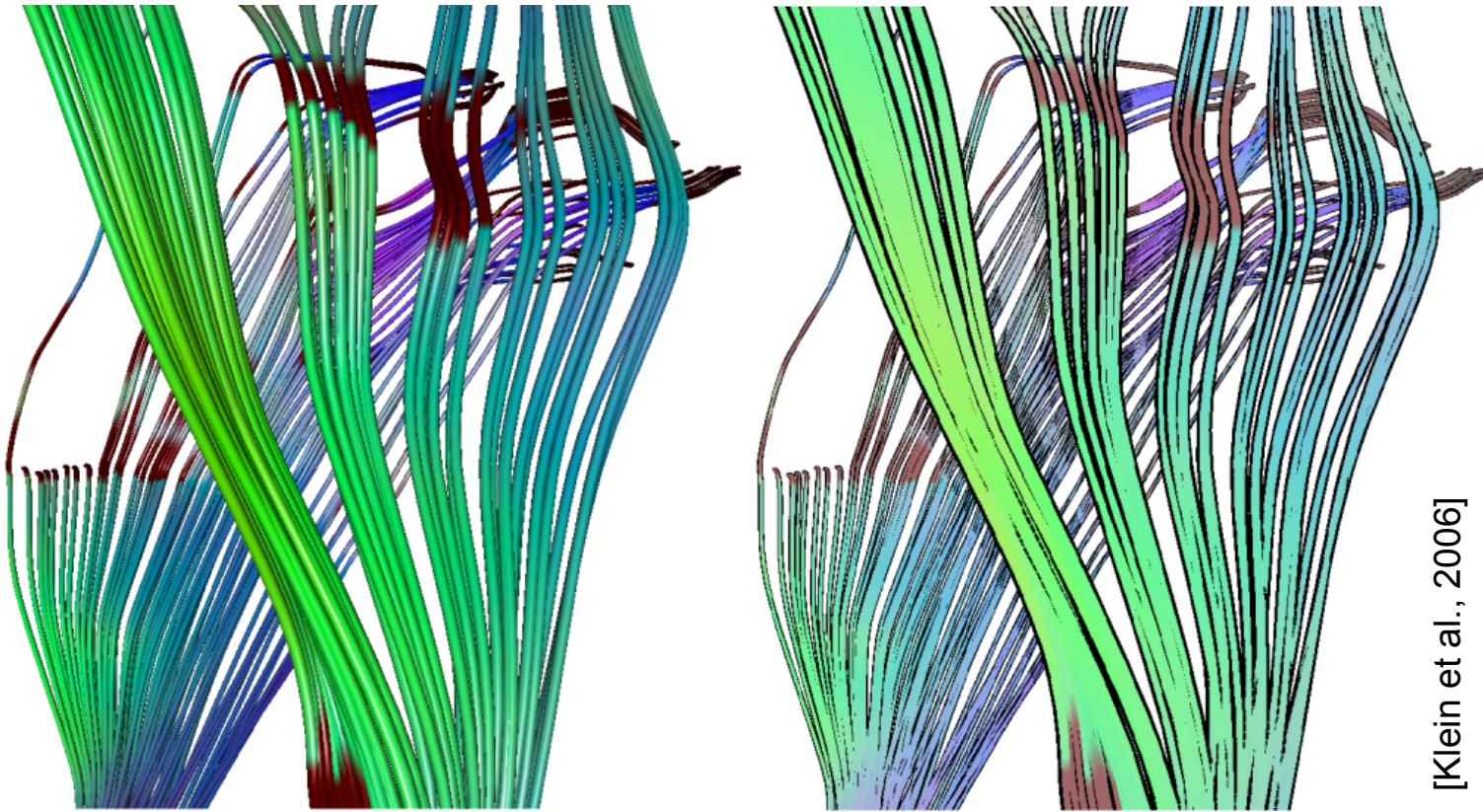
[Weigle and Banks, 2008]

Illustrative Visualization: Tubes with Halos



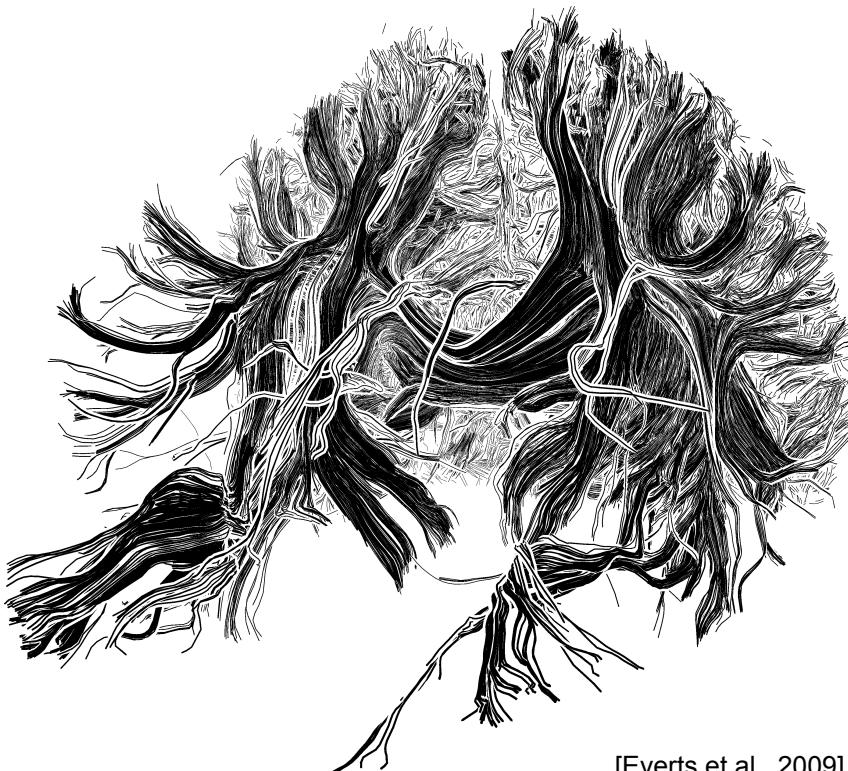
[Wenger et al., 2004]

Illustrative Vis.: Distance-encoded Contours



[Klein et al., 2006]

DTI Data: Line-Based Visualization

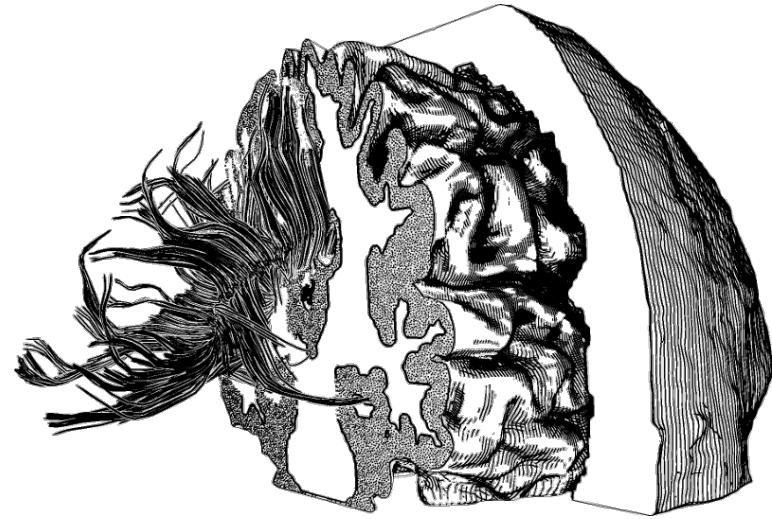


[Everts et al., 2009]

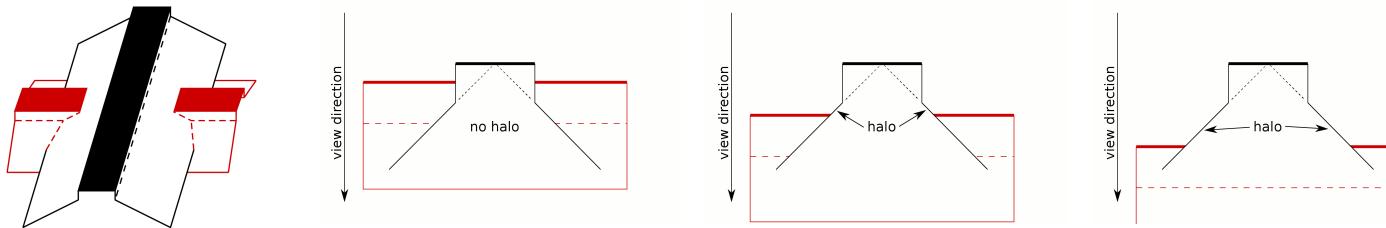
Line Strips + Depth-Dependent Halos



[Everts et al., 2009]

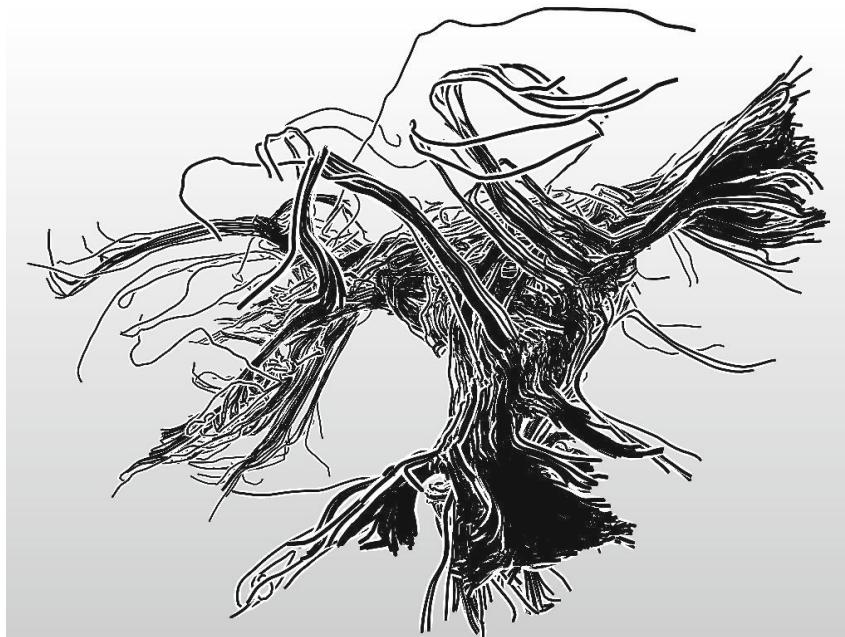


[Svetachov et al., 2010]

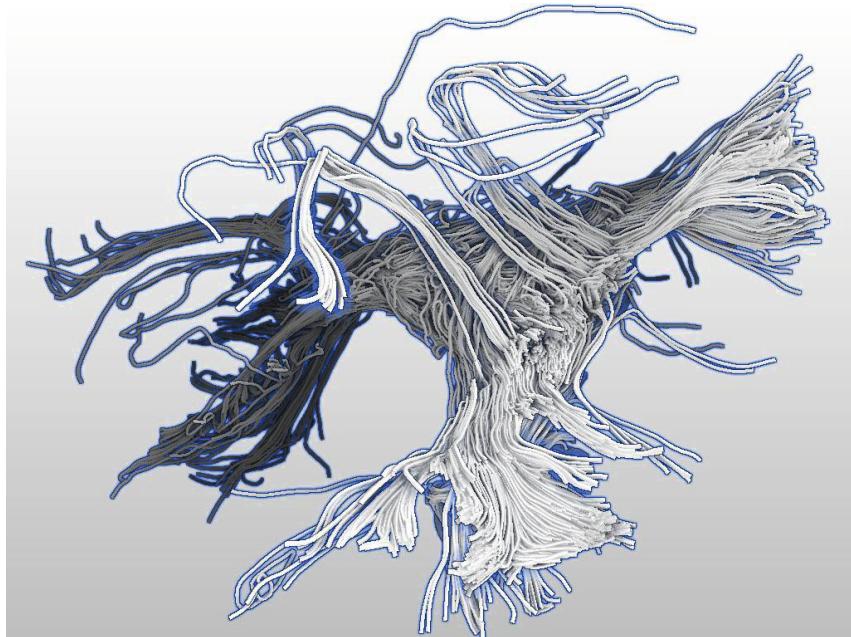


Lines & Ambient Occlusion (Sparse Data)

depth-dependent halos

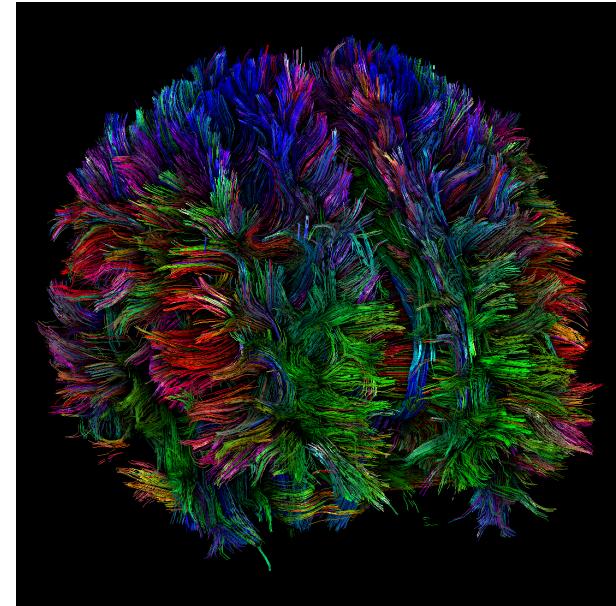
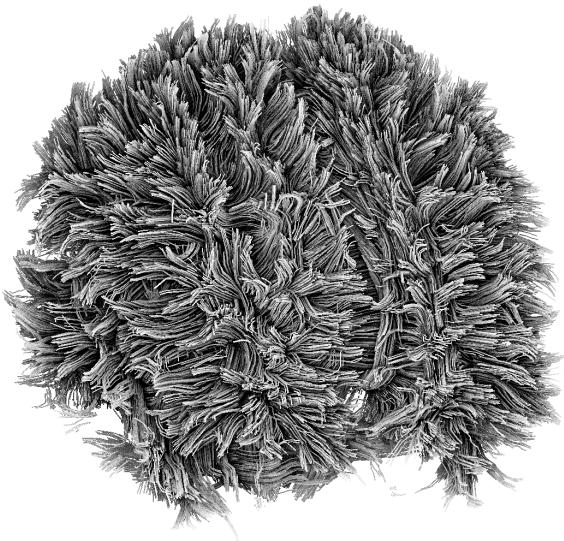
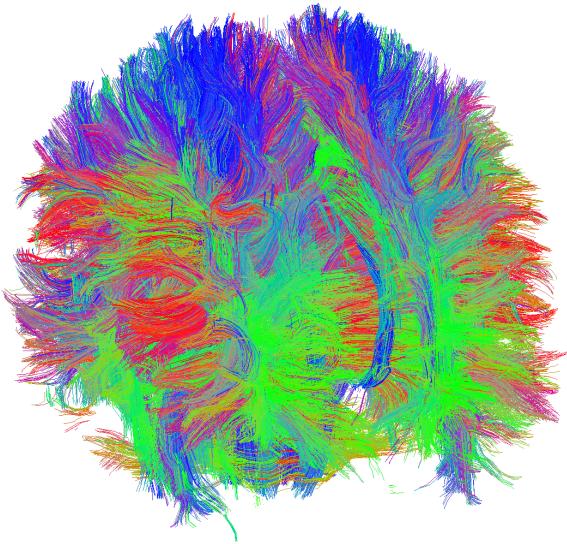


screen-space ambient occlusion



[Díaz-García & Vázquez, 2012]

Lines & Ambient Occlusion: LineAO



For dense line data: [Eichelbaum et al., 2013]

Conclusion

- Vision research provides plausible theories for the perception of transparency, flow, shape and depth.
- These theories were subject to various experiments.
- The experiments involve sufficiently complex geometric structures to transfer results e.g. to anatomy, biology.
- Visualization quality can be objectively assessed.
- Limitation of all experiments: rotation was disabled.

Outlook

- Feature lines may also improve depth perception in stereo condition
- Illustrative rendering also employed for improving augmented reality (Hansen, 2010)

Update

- Setting up shape and depth perception tasks is difficult, e.g. selection of stimuli, selection of sampling points where depth differences should be assessed
- Quality criteria for representative samples
- Guidance and example data:

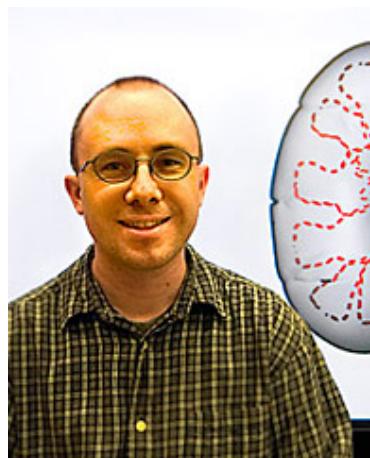
Meuschke, 2019: „EvalWizard“, *Computers & Graphics*
(extended version of Meuschke, 2018, VCBM, available online)

Limitation

- Perceptual evaluations relate to low-level properties
- Cognitive activities: Therapy planning, decision making, ...
- Small differences in shape or depth perception may be irrelevant for cognitive activities

Preim, 2018: „A Critical Analysis of the Evaluation Practice in Medical Visualization”, *Proc. of EG Workshop on Visual Computing in Biology and Medicine*

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Bernhard Preim, Alexandra Baer, Douglas W. Cunningham, Tobias Isenberg, Timo Ropinski: A Survey of Perceptually Motivated 3D Visualization of Medical Image Data. [Comput. Graph. Forum 35\(3\)](#): 501-525 (2016)

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