A Survey of Perceptually Motivated 3D Visualization of Medical Image Data

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EuroVis 2016
R. Maciejewski, T. Ropinski, and A. Vilanova
(Guest Editors)

Volume 35 (2016), Number 3
STAR – State of The Art Report

A Survey of Perceptually Motivated 3D Visualization of Medical Image Data

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Abstract

This survey provides an overview of perceptually motivated techniques for the visualization of medical image data, including physics-based lighting techniques as well as illustrative rendering that incorporate spatial depth and shape cues. Additionally, we discuss evaluations that were conducted in order to study the perceptual effects of these visualization techniques as compared to conventional techniques. These evaluations assessed depth and shape perception with depth judgment, orientation matching, and related tasks. This overview of existing techniques and their evaluation serves as a basis for defining the evaluation process of medical visualizations and to discuss a research agenda.

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Computer Graphics]: Picture/Image Generation—Line and curve generation

1. Introduction

The purpose of medical-image-data visualization is to support "the inspection, analysis and interpretation of patient data" and, more specifically, to enable "physicians to explore patient data rapidly and accurately with minimal cognitive effort" [ABK*15]. Medical image data, such as CT and MRI, are physical measurements which exhibit noise and inhomogeneities. The anatomical structures represented in the image data have organic shapes and may be quite complex (e. g., highly curved, branching). The spatial relations between the anatomical surfaces are often quite complex, which makes medical visualization problems unique. Although slice-based 2D visualizations dominate in the field of radiological diagnosis, there are many tasks—such as in treatment planning and in dealing with complex fractures–where 3D visualizations are employed (see [PP03] for a discussion of medical 2D and 3D visualizations).

A large variety of medical visualization techniques are available [PB14]. These techniques include basic surface and volume rendering techniques, tagged volume rendering to enable the selective emphasis of relevant objects, and smart visibility techniques [VKG05] to reveal important structures that may otherwise be occluded. Illustrative visualization techniques may be used to represent surface details faithfully [LMP13]. They may be combined with surface and volume rendering techniques [HBH03], display additional elements or details [Ise15], and generally facilitate the use of abstraction [RBGV08]. Special techniques were developed to clearly display elongated branching structures such as vasculature [JQD*08, KOCC14]. The rendering of fiber tracts extracted from Diffusion Tensor Imaging developed into its own research direction [Ise15] and a lot of research has been devoted to displaying blood flow [LGV*16, vPBB*10].

The above-mentioned techniques require users of visualization systems to adjust several parameters such as color, texture, or transparency to effectively represent tissue properties. Moreover, the final appearance depends on preprocessing (e. g., noise removal, vesselness filtering) and postprocessing (e. g., mesh smoothing or simplification). Consequently, the variety of methods, the resulting broad range of parameters, and the large number of possible parameter values—not to mention the impressive number of possible combinations—can be overwhelming for developers who want to create 3D visualizations for specific medical tasks.

Perception guidance. In general, visualization design decisions may benefit from visual perception research. For example, there is an extensive literature on contrast and shape perception, on the effectiveness of depth cues, on attentional guidance for goal-directed emphasis of important structures, and on other low-level (i. e., uses simple very visual information such as edges, contrast, color, motion, etc.), bottom-up (i. e., data-driven) processes that explain why some objects in a larger scene may be immediately recognized without special efforts. Moreover, it is clear that shading, shadows, and surface texture contribute to the perception of 3D shapes from images [Gib50]. While this basic research is an essential background for designing medical visualizations, it is by far not sufficient. Research in visual perception is (for good reasons) often focused on simple geometries and simple layouts with a few objects, and interaction is usually not taken into account. Thus, the results cannot be easily generalized to complex visualizations of irregular anatomical structures that are interactively explored by experts who know the particular anatomical region well.

Both Healey and Enns [HE12] as well as Ware [War12] provide a comprehensive summary of visual perception research and its consequences for information visualization. Similarly, Bartz and colleagues [BCFW08] discussed perception research and its consequences for computer graphics as well as virtual and augmented reality. Likewise, Thompson and colleagues [TFCRS11] discuss visual perception at length, with a focus on its applications to computer graphics. Pouli and colleagues [PCR13] have examined image statistics and their relationship to both perception and computer graphics. This survey extends these other reviews, in particular by adding an explicit focus on medical visualization. Thus, we discuss perceptual experiments that take realistic medical visualization scenarios into account, and we discuss the details of designing evaluation experiments in order to help the reader design experiments for concrete medical visualization problems.

Medical Tasks. In order to place this survey into an application-relevant context, it is necessary to consider the general functions that medical visualizations serve. In clinical practice, physicians *analyze* medical image data in a very goal-directed manner based on knowledge of clinical symptoms and previous examinations. They also use these images and derived visualizations to *communicate* with colleagues. Finally they sometimes, albeit much less often, freely *explore* medical image data without a clear hypothesis.

There are a number of general tasks for which 3D medical visualizations are used. They provide an overview when there is a rare anatomical variant or complex fracture. They are used for treatment planning; for example, making decisions about resectability (can a tumor be resected at all?), the amount of surgery, and access paths. For these tasks faithful representations of local regions including vasculature are required. The display of fiber tracts is essential for neurosurgery planning. Physicians are interested in local shape variations, for example in order to assess bones and possible rheumatic modifications [ZCBM14] or to assess the malignancy of a tumor. Possible infiltrations, such as the specific relation between a tumor and its surrounding structures, are also often essential. The investigation of anatomical details for selecting an implant has a similar level of complexity. These tasks require a thorough understanding of the relevant structures—including their appearance and shape—which makes it essential to take perceptual findings into account.

Scope and Organization. This state-of-the-art report (STAR) will focus on medical visualization techniques that display *one* dataset. Multimodal visualization, comparative visualization of datasets over time, or special data—such as functional MRI or perfusion data—are not considered here since there are very few perception-based studies for them. Blood flow and fiber tract visualization are considered, since there are a number of perceptually motivated techniques. Medical augmented reality is also not considered, although perception-based research is highly relevant there (see, e. g., Bichlmeier et al. [BWHN07]). Furthermore, we restrict ourselves to true 3D visualizations and do not discuss projections, such as colon flattening, or curved planar reformation [KFW*02]. This decision is motivated by the unique advantages and problems of 3D visualizations (e. g., occlusion). Furthermore, glyph-based medical visualization [ROP11] is not considered here, as it augments the anatomical 3D structures with artificial shapes. Moreover, we do not discuss the influence of display types such as stereo monitors [BHS*14].

The remainder of this STAR is structured as follows. In Sect. 2, we provide the basic findings of visual perception research that are relevant for medical visualization, with a particular focus on depth and shape perception. In Sect. 3, we introduce a number of perceptually-motivated, 3D, medical-visualization techniques, including volume rendering, vascular visualization, blood flow, and fiber tract visualization. In Sect. 4, we discuss general issues in experimental design with a focus on evaluating (medical) visualization techniques. This should not only help the reader to understand existing studies but also should provide guidance for designing new studies (and ensure that the results are valid). In Sect. 5, we come back to a selection of the techniques described in Sect. 3 in order to discuss how they were evaluated with respect to perceptual effectiveness. Since there is clearly a need for future research, we discuss a research agenda in Sect. 6.

2. Related Visual Perception Research

We discuss visual perception as it relates to medical visualization and focus on depth and shape perception, as these issues are crucial for 3D visualization. Color perception is also relevant for medical visualization since some types of medical-imaging data (e. g., histological images and cryosections) contain color. Color is also frequently used to display directional information, (e. g., in Diffusion Tensor Imaging), and velocity magnitude (e. g., in simulated and measured blood flow). Due to space constraints, we do not discuss color perception theories and their application. We also omitted visual search theories and related emphasis techniques.

2.1. Depth Perception

The study of depth perception is a core research area in visual perception with studies dating back to the late 1800's. It is clear that the speed and accuracy with which 3D scenes are perceived depends on depth cues [RHFL10].

Classes of Depth Cues. *Monoscopic depth cues* can be seen with a single eye. Shadows, perspective projection, partial occlusion, and shading are essential monoscopic depth cues. Motion parallax is one of the main motion-based, monoscopic depth cues. It exploits the image changes that occur when a 3D object or scene moves relative to the observer. There are a number of other motion-based cues (e. g., kinetic depth effect), all of which are collected under the term *shape-from-motion*. *Stereoscopic depth cues* employ the fact that the two eyes have slightly different views of the world. The two primary stereoscopic cues are binocular disparity (i. e., the difference in the location of an object in the two retinal images), and convergence (i. e., the angular deviation of the two eyes from straight ahead required to fixate on an object).

In addition to categorizing depth cues based on how many eyes they use (monoscopic versus stereoscopic), one can categorize them based on the class of information they use. In general, there are *motion-based* cues, *surface-texture* cues, and *illumination-based* cues. This last category is often referred to as *shape-from-shading* [Hor70, BCD*12] and follows the “Dark is Deep” paradigm [Nic41]. That is, the darkness of a small patch of a 2D image is directly related to the depth of that area in the 3D scene [TM83, Ram88, LB00].

Depth Cues in Stylization. In a photograph of the real world, a large number of monoscopic depth cues work together to provide explicit, metric information about the 3D layout of the scene, including information specifying that the input is a 2D image of a 3D scene. Careful attention to as many of these cues as possible allows us to synthesize photorealistic images. Using a subset of the cues still provides an effective way of clearly specifying the 3D structure of a scene without requiring full photorealism. Indeed, artists selectively use various image cues to create a stylized version of a scene. Naturally, computer graphics researchers have adopted and adapted the artist's stylized depth techniques. For example, the distance to a point on an object can be explicitly encoded by adapting line widths, by adapting the parameters of hatching techniques, or by indicating layering through halos [ARS79, BG07a, EBRI09].

Fig. 1 shows how some of these illustrative depth cues are used in medical visualization. The depth cues used here are based on real-world phenomena: silhouettes arising from grazing lighting (Fig. 1, left) and shadows from a camera-mounted light source (Fig. 1, right). Both of these cues are known to work acceptably well in humans, and are also used in computer vision models of shape-from-shading [BCD*12].

Beyond the effect of individual depth cues, there are a number of studies that examine the interaction between cues. For example, Zhai and colleagues [ZBM96] found that stereo projection and semitransparent volume cursors reinforced each other and enabled a faster and more accurate selection of objects compared to monoscopic rendering and opaque volume cursors. For more on depth perception research, the reader is directed to the overview books by Thompson and colleagues [TFCRS11] and by Goldstein [Gol02].

2.2. Shape Perception

The visual perception of 3D shapes is quite complex, in part due to the loss of information when the 3D object is projected to a 2D (retinal) image. Since the pattern of light on the retina is affected by an intricate interaction between the illumination and the geometry, orientation, and texture of the object, the same pattern of light sensations on the retina could have been caused by different 3D shapes. Thus, visual shape perception is inherently ambiguous. The ambiguity of diffusely shaded images, which is called *bas-relief-ambiguity*, cannot be resolved by any change in lighting [BKY97]. Despite this ambiguity, shape-from-shading is believed to be evolutionarily one of the earliest depth mechanisms and is very effective [KR92, ZTCS99]. The visual system relies on past experience and on several assumptions to resolve the ambiguities. For example, surfaces tend to be perceived as convex [CSD*09]. These assumptions are not always appropriate, and can cause incorrect perception of surface category and local orientation [Mar82]. Moreover, the most frequently used model of the human visual system [Ber87] assumes a single light source which is above and to the right [Bre44]. This assumption has significant consequences for many perceptual phenomena beyond shape perception. There is, however, some evidence that the human visual system may in fact inherently assume a number of (locally independent) light sources (see, e. g., [GKB*99]). Moreover, the visual system is remarkably insensitive to illumination inconsistencies under certain conditions [OCS05]. There is also evidence that the correct perception of material properties requires more realistic lighting conditions, such as multiple light sources [FDA03].

The perception of 3D shapes occurs at different spatial scales. At least two levels need to be distinguished [WB08]: a *local scale*, where the shape of individual objects is assessed and a *global scale*, where spatial relations, including depth relations and proximity of objects, are assessed. Indeed, there is considerable evidence that the human visual system represents the entire scene in a linear scale space, with a large number of scales, where each scale is a copy of the scene which has been convolved by a Gaussian kernel (and subsequent scales increase the size of the kernel; for more, see [PCR13]). Thus, research on the influence of depth cues should incorporate be aware of different scales.

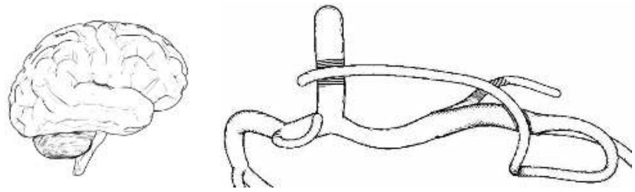

Figure 1: *Illustrative depth cues for medical visualization.* ***Left:*** *Brain depicted using silhouettes and ridge-and-valley lines that show discontinuities in the surface curvature (from [LP15]).* ***Right:*** *A vascular tree is depicted with a hatching style that indicates the distance between the front vessel and the occluded vessel (from [RHP*06], © IEEE, reprinted with permission).*

Shape-From-Shading. The changes in brightness along a surface can provide shape information. Depending on the illumination model, shadow areas represent strong discontinuities in brightness (for point light sources) or smooth transitions, such as soft shadows (area light sources). For complex anatomical surfaces, such as the brain with its many creases, advanced shadow generation using diffuse lighting improves the depth perception [Ste03]. The influence of the illumination model on perception was recently studied [HBM*14].

Shape-From-Texture. Most surfaces are textured. This can be seen as a violation of the assumption that neighboring parts of a surface affect light in the same way [Gib79] and it poses a problem for both edge-detection-based segmentation and shape-from-shading techniques. Texture can, however, provide information about shape. Altough a considerable amount of information exists about the large-scale structure of images [PCR13], most of the information about textures is implicit (such as the structure of the Fourier transform of an image). One of the earliest examinations of texture is from Gibson [Gib50]. The most influential model of texture structure comes from Julesz and Caelli [JC79, Jul81], which models texture elements as Gabor patches (a sinusoid convolved with a 2D Gaussian). Interestingly, Gabor patches bear a strong resemblance to the receptive field structure of human vision. Texture is particularly useful in determining the local curvature of a surface [TFCRS11]. For example, surface textures that represent principal curvature directions (PCDs) improve shape perception: observers tend to interpret lines on a surface as curvature directions [ML98, Ste81].

In visualization, texture has been used to represent essential properties of shape. Lines on a surface may help the viewer to separate it into meaningful substructures. If shapes are familiar, viewers look for features that enable such a separation. Interrante and colleagues have shown that a certain type of line—frequently used by illustrators—supports this separation [BHS89, IFP95]. These lines are called *valley lines* and represent regions of a curved surface, where the curvature along the PCD has a local minimum (i. e., the location, where the surface is flattest). These regions are heavily affected by occlusion of surrounding structures and are thus drawn with dark colors. If there are not enough features that can be displayed with valley lines, *ridge lines* may be added, representing regions with a local maximum of the curvature along the PCD (i. e., the regions, where the surface curvature is highest; see [LP15] for mathematical descriptions of—and algorithms to compute—these lines). Such a sparse representation of a surface may be useful in displaying an outer surface in a multi-layer visualization (e. g., to display an organ surface and a deep-seated tumor as well as surrounding risk structures). This is a promising alternative to a semi-transparent display, where the ordinal depth cues, such as occlusion and shading are hardly recognizable for a transparent surface [IFP95].

There is some debate about whether texture cues can be interpreted correctly when a 3D model is displayed in orthographic projection (a typical situation in medical visualization). Li and Zaidi found that "the surface must be viewed with a noticeable amount of perspective projection" [LZ01]. Kim and colleagues [KHI04], however, found that curvature-directed lines convey shape even with orthogonal projection. Using only ridge lines may be "uninformative" if most of them are almost aligned with the viewing direction. Thus, a combination of ridge and valley lines yields better performance [SW04].

Shape From-Silhouettes. Most physiological studies on the neural basis of early visual processing show that one of the first steps in the visual cortex is to extract edges [HW68, Tho00]. Edges are critical for segmenting an object from its background, and as such they are important for both human vision and for visualization. The explicit display of silhouettes [IFH*03]—as boundary between an object and the background—supports object recognition. The display of silhouettes is particularly effective in low-contrast regions with a high density of objects. In medical visualization, this gives rise to the incorporation of edge detection and boundary emphasis techniques [CRD10, KWTM03].

Combining Cues. Depth and shape perception benefit from combining several depth cues that tend to reinforce each other instead of being just redundant [BC88, IFP96]. As an example, the combination of silhouettes and surface textures is effective [GIHL00]. However, combining cues does not always improve perception and may even hamper it, as in case of various feature lines [CRD10].

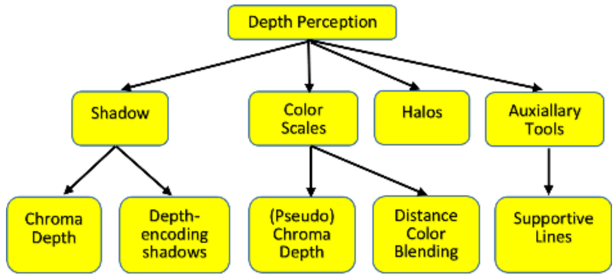

Figure 2: *Illustrative depth perception techniques use shadow, depth-dependent color scales, halos, or auxiliary tools.*

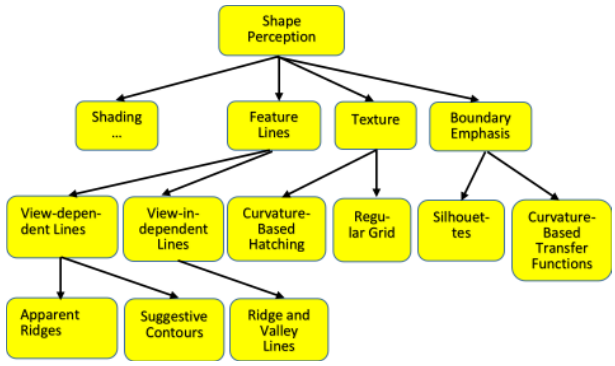

Figure 3: *Illustrative shape perception techniques are based on shading, line drawing, texture, or boundary emphasis.*

3. Perceptually Motivated Medical Visualization

In this section, we discuss selected examples of visualization techniques that have been applied to medical image data and are motivated by the considerations discussed in the previous section. We briefly discuss high level results from evaluations. Detailed descriptions of evaluation methods and results are postponed to Sect. 5.

Selection Strategy. Our selection is based on a search in the following digital libraries: ACM DL, IEEE Xplore, and Eurographics. Based on an initial selection of relevant papers we derived the keywords "perception" or "depth-enhanced" on the one hand, and "graphics" or "visualization" on the other hand. In particular, papers discussing depth perception, often use the term "depth-enhanced", whereas papers discussing shape perception are found with a search for "perception". Papers related to augmented and immersive virtual reality, virtual environments, and information visualization were not considered. Papers related to application areas other than medicine (e. g., automotive design), were also not considered. Many papers discuss perception-based visualization in a quite general way. From these papers, we selected those with medical examples and careful discussions of the peculiarities of medical image data and their use.

We found two major trends, focusing on the perceptual consequences of

- global illumination and physics-based lighting and
- illustrative techniques inspired by medical illustrators and aesthetics consideration.

To provide a basis for selecting perceptually-motivated visualization techniques for a specific medical task, we have structured our review based on major applications for which perceptually-motivated visualizations have been developed: volume visualization, vascular visualization, visualization of flow, and fiber tract visualization.

3.1. Volume Visualization

Corcoran and colleagues [CRD10] stated that "rendered images of complex volume data tend to have excessive detail, which is often multilayered and overlapping. [...] a perceptually challenging type of visual output." Accordingly, in the past decade a large number of techniques have been developed to improve shape and depth perception in the 3D visualization of medical volume data. Following the two trends mentioned above, we consider physics-based and illustrative techniques. Within the physics-based group, we discuss techniques that mimic some aspect of the physical world, such as light transport or refraction in the eye. The illustrative group, on the other hand, consists of techniques that exploit stylization and are often artistically inspired. Since no individual technique is ideal for shape *and* depth perception, we support the reader in selecting the right techniques by providing an overview of the techniques which support depth perception (see Fig. 2) and those which support shape perception (see Fig. 3). The shape perception techniques that are based on shading are shown in a separate diagram (see Fig. 4). In the following, we will discuss these techniques in greater detail.

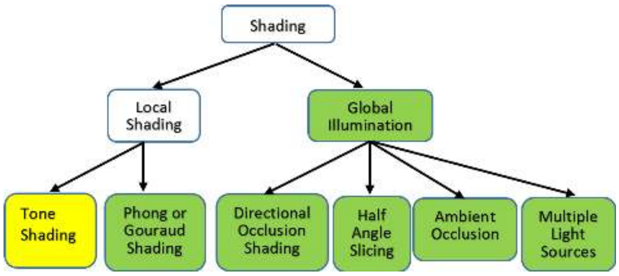

Figure 4: *Shape perception techniques based on shading. Yellow rectangles represent illustrative techniques and green rectangles physics-based techniques.*

3.1.1. Physics-Based Techniques

Physics-based techniques mimic the physical effects that underly light transport. This can be the exploitation of how light enters the viewer's eye or how light is distributed in a scene.

Aerial Perspective Techniques. Aerial perspective is the simplest of the physics-based techniques. It simulates the effects of haze or fog in an environment by modulating colors based on the distance to the viewer [OBO94]. Thus, it can be considered as a direct color-modulating depth cue. Usually, it complies with the "Dark is Deep" paradigm [LB00, TM83], and distant structures are colored darker than nearby ones. Distance color blending [ER00] aims to further improve the aerial perspective by computing the color of a structure as a distance-weighted combination of its original color $color_{orig}$ and a background color $color_{background}$:

$$color = (1-d)\cdot color_{orig} + d\cdot color_{background} \qquad (1)$$

Ebert and Rheingans [ER00] showed that this weighting does not need to be linear—exponential functions can be employed. In their application scenarios, the background color is often blue. This is inspired by artists who use blue backgrounds to depict an aerial perspective. Svakhine et al. [SEA09] enhance depth perception for large- and small-scale features by employing color-based techniques which also mimic the effects of the aerial perspective. To give the user more control over how features are emphasized, Svakhine et al. introduce a depth filtering function, which allows depth enhancement to be constrained to a subset of the overall depth range.

Illumination-Based Techniques. The second group of physics-based techniques focus on illumination. These techniques exploit the peculiarities of light transport and the fact that the human visual system has evolved to interpret the effects resulting from the underlying physics. Thus, shadowing, shading and other effects play an important role in this group of techniques. Volume rendering with advanced illumination-based techniques was recently introduced in commercial medical diagnosis software (e. g. SIEMENS syngo.via Frontier) and is referred to as *cinematic rendering*. In addition to lighting effects, light source placement affects shape perception considerably. While lighting design for polygonal surface rendering was studied in depth (see [SL01] for a seminal contribution), it recently attracted interest in (medical) volume visualization [TLD*12, ZWM13, ZCBM14].

Aerial perspective could also be considered an illumination-based technique, as it is based on the attenuation of light. Due to the striking similarity to chromadepth, however, we have classified it as chromadepth-based technique.

In the following, we will briefly discuss other illumination-based techniques as they are often applied in 3D medical visualization. While most of the techniques follow the widely-spread, gradient-based illumination model proposed by Levoy [Lev88], a large number of illumination models that consider shadowing, ambient occlusion, halos have recently been proposed.

Shadowing Effects. Due to the importance of shadowing effects in depth perception [WFG92], shadows are often taken into account in perceptually-motivated volume rendering. Due to the computational complexity of these lighting effects, algorithms are often constrained to single scattering and to the use of a point or a directional light. To optimize the required computations, several approaches have been proposed in the area of medical visualization. One of the first interactive algorithms taking into account global illumination effects in direct volume rendering was the half-angle slicing technique [KPH*03]. While lights can often be placed freely, a special case exploits headlights which are fixed at the camera position [SPH*09]. Multidirectional occlusion shading [SPBV10] enables flexible lighting (i. e., the light vector is not restricted to be parallel to the view vector), which enables significantly better shape perception (e. g., with lateral or oblique light vectors). In contrast to these techniques—which exploit sequential processing in slice-based volume rendering—newer techniques integrate global illumination into other volume rendering paradigms (e. g., image plane sweep volume illumination for GPU-based raycasting [SYR11]). A comprehensive overview of recent global illumination techniques for medical data can be found in the survey of Jönsson and colleagues [JSYR14].

Ambient Occlusion Effects. While shadows can be considered as uni-directional lighting effects, ambient occlusion techniques simulate the occlusion that blocks light reaching a structure from all incoming directions. In contrast to single scattering shadowing techniques, ambient occlusion results in a more subtle effect, which resembles the appearance of diffuse materials under environmental lighting. Due to the added value in shape perception [LB00], it has also been applied in the area of medical visualization [RMSD*08, DVND10]. Local Ambient Occlusion is a local approximation technique which considers only the voxels in a neighborhood around each voxel [HLY07].

Lighting Parameters. The placement of light sources affects shape and depth perception [BBC83]. A combination of different light sources enables a better recognition of surface details than a default light source placed at the top of the scene. Tao and colleagues [TLD*12] introduced a quality metric for lighting effects that includes

- lighting goodness,
- lighting similarity and
- lighting stability.

Lighting goodness assesses the quality of lighting basically by analyzing differences between an unilluminated image and an illuminated one. Lighting similarity measures whether a light source is highly representative, which is desired for the placement of several light sources to ensure that they complement each other well. Finally, light stability refers to the differences that result when a light source position slightly changes. Ideally, the depiction of an object's shape is robust against small positional changes. Tao and colleagues employ this metric to optimally place an initial light source and then to add additional sources as long as they improve the recognizeability of shapes (according to their metric of shape perception). In their perceptual experiment, participants were asked to compare pairs of images with respect to recognizability of surface details. In most cases, images, where the light sources were optimized were rated as better than images with randomly placed light sources. The new metric turned out to be superior to optimizations based on other metrics (e. g., from Gumhold and colleagues [Gum02]). These results are also true for the medical volume data.

The following setup for light sources has been shown to be perceptually effective:

- a *key light* with high intensity at the top left of the scene,
- an auxiliary *fill light* placed in front of the scene, and
- a *back light* that emphasizes the silhouettes.

The back light should be blue and the other light sources should be white. The key light should have the highest intensity and the back light should have the lowest. One drawback of this configuration is that some thin structures may be overexposed [ZWM13]. One possible remedy is to use a global tone mapping. This configuration was used in a case study on the analysis of rheumatoid changes. The lighting configuration was perceptually evaluated and discussed with respect to a specific diagnostic task, namely the detection of small erosions from rheumatoid arthritis [ZCBM14]. Zheng and colleagues compared local and global illumination and found that local illumination depicts excessive detail, whereas global illumination leads to a softer appearance resulting in a lower rate of false positives. With this type of lighting and global illumination, the number of diagnostic errors decreased considerably and participants were twice as fast. It is also important to mention that the participants (who were all physicians) wanted to see both the globally illuminated data and the locally illuminated data. In addition to surface orientation and category assessment tasks, Zheng and colleagues employed lighting-specific metrics [ZWM13] to measure the degree to which—under different lighting conditions—the luminance histogram was nearly equalized and the degree to which edges (based on an edge detector) were very salient.

Perceptual Benefits. Several studies have been conducted to investigate the effects of advanced volume illumination techniques on depth and shape perception. Lindemann and Ropinski [LR11] have compared seven state-of-the-art volumetric illumination techniques with respect to depth and size perception as well as to subjective preference. They presented participants with volume-rendered images generated using different illumination models and asked the participants to perform depth, size, and beauty-judgment tasks. The results indicate that global illumination improves the perceptual qualities of volume-rendered images. In particular, directional occlusion shading [SPH*09] improved depth perception significantly. Interestingly, participants nonetheless had a subjective preference for the simple gradient-based shading technique.

Šoltészová and colleagues [SPV11] investigated the influence of shadow chromaticity through depth testing and found that shadow chromaticity influenced the perceptual qualities of volume-rendered images. In another work by Šoltészová and colleagues [STPV12], shape perception for complex slanted shapes—such as they occur in anatomy—was analyzed. Like previous authors, they found a systematic error in estimating surface slant. They also discovered that upwards-pointing normals are underestimated less than downwards-pointing normals. This finding enabled them to automatically adjust the shading scheme to correct for these errors. In a follow-up experiment, they showed that shape orientation was indeed more precisely perceived after the correction. More recently, Diaz and colleagues [DRN*16] investigated the influence of global volume illumination techniques in desktop-based VR systems and found a positive effect on depth perception.

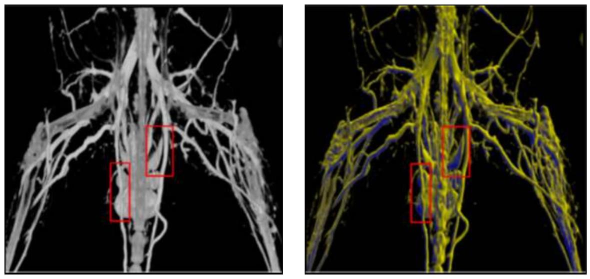

Figure 5: *Comparison of normal shading and toon shading.* ***Left:*** *Vascular tree rendered with standard volume rendering.* ***Right:*** *Same data set rendered with toon shading (from [JQD*08], © IEEE, reprinted with permission).*

3.1.2. Illustrative Techniques

Illustrative techniques do not aim to mimic the real world, but instead borrow from art and illustrations [And96,Hod89]. This class of technique often helps to guide the viewer's attention in a goal-directed manner, emphasizing important aspects and suppressing or omitting other aspects. Selected examples, such as boundary emphasis, tone shading, feature lines, and texturing will be discussed in detail below.

Boundary Emphasis. Boundary emphasis—usually as a contour—has shown much promise in enhancing volume rendering, presumably since silhouettes play a central role in object recognition. Early methods evaluated (only) the angle between the surface normal n and the view vector v, emphasizing regions, where the dot product of these vectors was close to zero. Unfortunately, the width of the contour cannot be controlled in this technique. Kindlmann and colleagues [KWTM03] solved this by analyzing the normal curvature in the viewing direction and then using this value to regulate contour thickness. While this method produces perceptually meaningful renditions, it requires curvature values (second order derivatives). A more computationally-effective solution was introduced by Bruckner and Gröller [BG07b]. Despite the fact that this latter method is not accurate—since curvature is only approximated by the change of normal directions—it is sufficient for creating expressive visualizations from volume data.

Toon Shading. Many forms of medical image data—such as CT, MRI and PET—have no inherent color. Thus, color may be used to enhance the shape perception. A widespread strategy is to map the surface direction (approximated as normalized gradients in direct volume rendering) with a cool-to-warm color scale. This illustrative-rendering technique was introduced by Gooch and colleagues [GGSC98] and is also used in medical visualization [JQD*08]. In RGB space, the cool color uses a non-zero blue component, while the warm color is based on yellow and uses the red and green components:

$$color = K_{cool}(1+L\cdot N)/2 + K_{warm}(1-(1+(L\cdot N))/2) \qquad (2)$$

with L being the light vector, N being the surface normal or normalized gradient, $K_{cool} = (0,0,T_{cool})$, and $K_{warm} = (T_{warm},T_{warm},0)$. Fig. 5 clearly shows that toon shading improves the shape perception.

Chromadepth. The selection of blue as background color in distance color blending [ER00] is very consistent with perceptual considerations since the light-sensitive cells that respond to blue col-

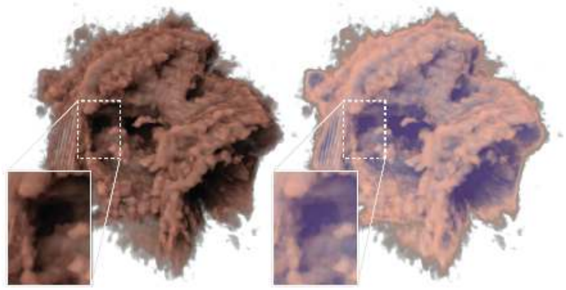

Figure 6: *Visualization of cardiac ultrasound data.* ***Left:*** *A black shadow color is used.* ***Right:*** *A blue shadow color adds a color contrast in shadow regions. The differences are obvious in the close-up region (Courtesy of Veronika Šoltészová, University of Bergen).*

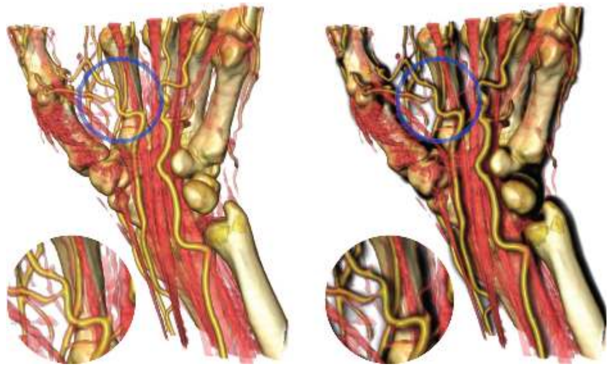

Figure 7: *Halo effects in direct volume rendering.* ***Left:*** *Standard direct volume rendering of a CT scan of a human hand.* ***Right:*** *Same data set with dark halos applied (from [BG07a], © IEEE, reprinted with permission).*

ors primarily have a slow response time. Furthermore, the lens of the eye refracts colored light with different wavelength at different angles. Thus, the refraction of blue wavelength light at the eye's lens can result in an offset of the retinal image, which makes these objects seem to be further away than, for instance, red objects. Thus, the blue background naturally supports the focus on the foreground, which is typically rendered in red. This effect, called *chromadepth*, is employed for stereo perception (with diffraction grating glasses). It can also be used, however, for depth perception without glasses [Ste87], if the depth value is mapped to the rainbow color scale (red is proximal, blue is distal). Due to these benefits, chromadepth-based techniques have also been applied in medical visualization [RSH06, BGP*11, SPV11].

One central application of chromadepth is to improve the depiction of shadows. The realistic simulation of shadows darkens the affected regions so strongly that there is often next to no contrast there, effectively hiding any information present there [SPV11]. Šoltészová and colleagues noticed that illustrators often do not mix the object color with black, as shadowing algorithms do. Instead, they prefer to mix the original color with blue such that shadowed regions have a luminance and a color contrast. Šoltészová and colleagues suggested that *shadowiness* is mapped using an appropriate transfer function to a blueish color and to opacity. The specific color scale is derived from the perceptually motivated CIELAB color space, where the Euclidean distances roughly correspond to our perception of color differences. With this *shadow transfer function* they effectively compensate for the lower luminance range in the shadow region, and thus reveal more details by avoiding black concavities. This is an inspiring idea, as it mixes a depth cue from real-world perception (shadow) with an artificial depth cue (since the color assignment clearly deviates from physical illumination). The method was applied to a variety of medical datasets, including CT and ultrasound data. Fig. 6 illustrates the difference between chromadepth and conventional shadows. This kind of shadow generation is similar to illustrative cool-warm color shading [GGSC98].

Halo Effects. Halos can be thought of as the opposite of shadows: shadows arise when occluding structures decrease the amount of illumination received by adjacent objects while halos are rim-like structures that shine on adjacent objects. Since halo effects are designed to support depth perception, the foreground features are usually emphasized with a bright surrounding halo [ER00]. The background object is made less prominent by making the surrounding more opaque or darker. When the halo color is dark, halos closely resemble shadowing effects. This well-known artistic technique was first applied in visualization in the context of flow visualization [IG97, IG98]. There, the halo effect was computed per voxel by adding halo influences in the neighborhood. Fig. 7 shows an example, where halos are applied to medical volume rendering.

Feature Lines. As mentioned above, object outlines and boundary emphasis techniques can improve the space perception. In addition to the outer object boundaries, a variety of lines exist to represent discontinuities in visibility, surface normal, curvature, and illumination. Generally, two classes of feature lines exist:

- view-independent lines and
- view-dependent lines.

View-independent features are solely influenced by the shape of an object, and as such they are the same for different vantage points. These include crease lines based on "large" dihedral angles between adjacent faces and the previously mentioned ridge and valley lines (e. g., [IFP95, OBS04]) that are derived from second-order features (curvature) and are very sensitive to noise.

In contrast, view-dependent feature lines take the view direction (and sometimes the illumination) into account. Among the view-dependent feature lines, *suggestive contours* [DFRS03] and *apparent ridges* [JDA07] have been frequently used in medical visualization [CRD10, LBSP14]. Suggestive contours [DFRS03] characterize regions in a surface that would be silhouette regions if the viewpoint of the camera was to change slightly. Thus, they provide continuity during interactive exploration. Apparent ridges [JDA07] are view-dependent versions of the static ridge-and-valley line concept: They extend the definition of ridges with a view-dependent curvature term. In interactive exploration, apparent ridges thus adapt to the viewing direction and slide over a surface instead of being constant. In contrast to suggestive contours, apparent ridges also include lines in convex regions. Both suggestive contours and apparent ridges have a *relevance threshold* that can be adjusted for drawing or suppressing lines. Fig. 8 compares these feature lines.

For static images, it has been shown that both classes of feature lines can give similar results for shape perception tasks [CSD*09]. Nonetheless, it is generally accepted [DFRS03, JDA07, CGL*08, LBSP14, LP15] that view-dependent feature lines are better for line drawing in general than view-independent lines. View-independent

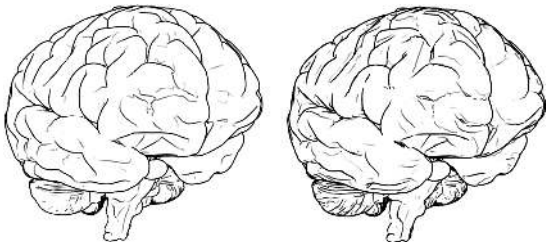

Figure 8: *Suggestive contours (left) and apparent ridges (right) applied to a brain model. Although they slightly differ, both represent the shape of the brain well (Courtesy of Kai Lawonn, University of Koblenz-Landau).*

ridge-and-valley lines are subject to noise [LP15], "seem to exaggerate curvature" [CGL*08], make features "look overly sharp" [JDA07] or "like surface markings" [DFRS03], and due to being locked to the surfaces they are easily occluded by the very features they represent. Only for mathematically ideal shapes with unrealistically sharp features (3D models of implants are a typical medical example) can static ridge-and-valley lines be equivalent to view-dependent concepts, such as apparent ridges. For organic shapes, in particular models obtained from medical scans, a large amount of smoothing needs to be used to avoid problems with view-independent lines. For specific recommendations on which view-dependent or -independent line concept should be used, we refer the reader to the survey of Lawonn and Preim [LP15].

Silhouettes [IFH*03]—which are view-dependent lines on the surface of an object—were employed along with surface and volume rendering [TIP05] to display context objects in a sparse manner to support attention to the focus objects (see Fig. 9). Corcoran and colleagues [CRD10] adjusted two-level volume rendering to incorporate object-space silhouettes and suggestive contours. Overall, shape perception was improved with both feature line techniques.

By far the most comprehensive evaluation of the perceptual effectiveness of feature lines was performed by Cole and colleagues [CSD*09] who performed an experiment with 275.000 gauge figure measurements using Amazon's mechanical turk. They investigated all major features lines (including apparent ridges and suggestive contours) and compared them with shaded images and illustrations performed by an artist. Among the twelve models used in the study were four (partially) complex anatomical structures (including the cervical bone, a vertebrae) and two less complex models (a tooth and a femur bone). The major results of that study are:

- There are statistically significant differences between almost all pairs of feature line techniques.
- All feature line techniques were less effective than shading (for all 12 models).
- Shape perception was poor for the anatomical models with any type of feature line (even with ridge and valley lines, where the mean deviation was 35°, compared to 24° with shading).

As a consequence, the sole use of feature lines for displaying single anatomical structures is perceptually not recommended.

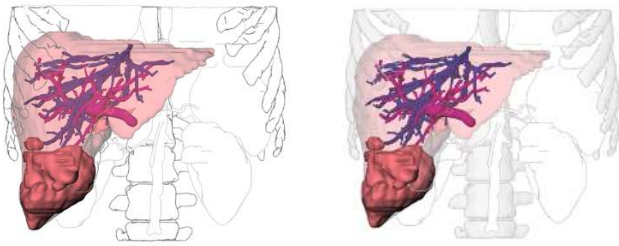

Figure 9: *The focus objects—a liver tumor and the vascular trees of the liver—are displayed as colored, opaque objects. The liver surface is a near-focus structure rendered transparently but also colored. Other organs and skeletal structures are rendered with silhouettes. In the right image, skeletal structures are rendered also as strongly transparent shaded surfaces (from [TIP05]).*

Hatching. Shape representation using feature lines can yield images that are too sparse when the shapes have only a few landmarks, such as is the case for the liver and the kidney. When an appropriate surface parameterization exists, hatching textures may improve shape perception. The strokes of such a hatching texture are more regularly distributed over a surface. The strokes are fully opaque, whereas the remaining elements of the texture are fully transparent. Obtaining an adequate surface representation is challenging, especially if surface models are derived from (noisy) medical-image data. Usually, mesh smoothing must be performed.

The perceptual benefit of hatching strokes is influenced by the amount to which they "follow the shape," especially for organic (curved) shapes [LZ01]. One of the earliest applications of this principle comes from Saito and Takahashi [ST90], who applied regular hatching lines (latitude and longitude lines) to curved surfaces.

Hatching has been shown to improve shape perception when it is used in combination with conventional shading with a local illumination model. It was also successfully used (based on experiments) for multi-layer medical visualizations [IFP95]. It is unclear how well hatching works in isolation, as this has rarely been investigated. Hatching—like feature lines—may be stylized (i. e., parameters may be mapped to line style, width, brightness, or even color hue). This can be used to discriminate objects (e. g., by different hues) or to encode depth explicitly. So far, there has been no experimental comparison of feature lines, hatching, and shaded surfaces for anatomical surface models with respect to shape perception. Currently, one may *suppose* that the joint use of shading and appropriate hatching yields better performance than shading alone or feature lines alone. How a joint use of feature lines and shading would perform is also not known. The only comparison of feature lines, hatching, and shading that we are aware of was performed for moving objects with very simple shapes that do not resemble anatomy [WFGS07].

Interrante and colleagues [IFP96] discussed another strategy that is more concretely rooted in perceptual research [Koe90]: they created strokes that indicate the local curvature of the surface. For this purpose, they computed the two PCDs and their respective scalar values. This computation results in two vector fields: a vector field representing vectors with maximum curvature and a second field with orthogonal vectors representing minimum curvature. The actual placement of the strokes is essential to the successful use of curvature-based hatching. The strokes provide essential shape cues in regions, where there is a considerable curvature. In flat regions, maximum curvature directions are unreliable, and therefore no hatching strokes should be generated there. Thresholding is thus necessary to avoid perceptual problems.

Sweet and Ware [SW04] examined the perceptual effectiveness

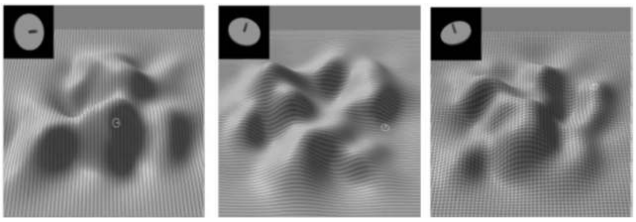

Figure 10: *An undulated surface, where brightness reflects the illumination and various textures are overlaid. Shape perception experiments used a gauge figure task (enlarged gauge figures can be seen in the corners of each image). From left to right: shading enhanced with parallel vertical lines, shading and parallel horizontal lines, and shading enhanced with a regular grid texture (from [SW04]).*

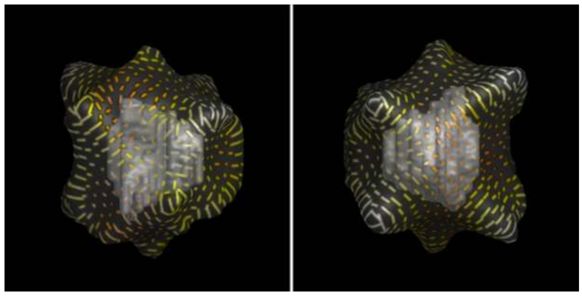

Figure 11: *The inner surface represents a tumor and the outer surface an isosurface resulting from the dose simulation in radiation treatment planning. Both are shown together in order to assess whether the tumor is likely to be completely destroyed. The outer surface is rendered as a strongly transparent isosurface enhanced with curvature-directed strokes (from [IFP97], © IEEE, reprinted with permission).*

of parallel lines on surfaces in all three directions separately and compared it with a regular grid composed of parallel lines in two directions. In their large study, the average angular deviation was 20 degrees for surfaces that had only shading information. All types of line-based enhancements improved accuracy scores. The best results were achieved with a regular grid texture (angular deviation was reduced to 12 degrees). The regular grid texture even produced significantly better performance than overlays with horizontal and vertical lines. Fig. 10 depicts three of the six viewing conditions.

Hatching Textures for Nested Anatomical Surfaces. Hatching textures are particularly useful for multilayered visualizations, especially when they are used to depict the outer shape in a manner so that the display of the inner shapes is only minimally occluded. Thus, instead of a semi-transparent outer surface, a small set of opaque strokes—indicating the surface location and its curvature—represents the outer surface. Interrante and colleagues applied this strategy to medical surface models (e. g., to indicate the dose distribution of simulated radiation treatment planning in anatomical models). In their first system, they used a hatching texture created from ridge and valley lines [IFP95]. Unfortunately, not all dose distributions could be conveyed with these sparse feature lines. More evenly spaced curvature-directed hatching lines better revealed the outer surface [IFP97]. In a series of experiments, they showed that hatching textures with lines that follow the PCDs conveyed the local orientation of smooth curved surfaces with convex and concave regions better than Phong shading [IFP96, IFP97, KHI04]. Fig. 11 shows an example of the stimuli from these experiments.

Hatching Medical 3D Visualizations. Hatching techniques in medical visualization may be adapted to the specific anatomical objects. The display of muscles, for example, benefits from hatching textures representing their fiber structures [DCLK03, TPB*08]. Elongated structures, such as vasculature and long bones, are hatched orthogonally to their local centerline (following the tradition of medical illustrations [And96]). These papers discuss generating high quality surface and volume textures, but do not perform any perceptual experiments or evaluations.

3.2. Vascular Visualization

Many different 3D vessel visualization techniques have been developed to support the treatment planning. One family of vessel visualization techniques employs direct volume rendering and uses a transfer function to emphasize vascular structures [JQD*08, KGNP12]. While most of these techniques serve to enhance preoperatively acquired images, the technique by [WSzBD*14] is aimed at incorporating depth cues for improving interventional images of vascular structures. A second family of techniques reconstruct a surface mesh of vascular structures with explicit, implicit, or parametric visualization techniques (see, e. g., the survey of Preim and Oeltze [PO08]). In the present survey, we do not consider the different geometric approaches, but assume that a smooth and accurate surface mesh is available. We do, however, discuss different ways of displaying this surface mesh (e. g., with illustrative methods).

Vascular visualization has the same requirements as other 3D visualizations as well as a few new ones (this is particularly true wen the visualizations will be used for treatment planning): [RHP*06]:

- the spatial distance between vessel segments is essential (e. g., indications of when one segment occludes another);
- the discrimination of vascular systems is needed since vessel segments can belong to the arterial or the venous system;
- the spatial distance between lesions (e. g., tumors) and vessel segments is essential, especially if the vessel segments exhibit a larger diameter; and
- during treatment planning, the exploration of vascular trees should be possible. During surgery, on the other hand, static images are desired in order to better reveal the important information at a glance.

The visualization techniques described in the following are driven by these requirements. All of them are *illustrative*. Since vascular structures are particularly complex shapes, it comes as no surprise that the basic, perceptually-motivated techniques (recall Sect. 2), such as chromadepth shading, distance color shading, toon shading and halos are used [RSH06, JQD*08]. The effect of distance color blending (with blue as distant color) is shown in Fig. 12.

3.2.1. Illustrative Shadows and Textures

While the depth order in vascular trees is obvious with conventional visualization techniques using occlusion as a depth cue, the distance between the frontal vessel and the occluded vessel cannot be assessed reliably. Ritter and colleagues [RHP*06] modified a stripe texture to illustrate distances between branches of vascular structures or distances between branches and surrounding structures (recall Fig. 1, right). Motivated by *vicinity shading* [Ste03]—a

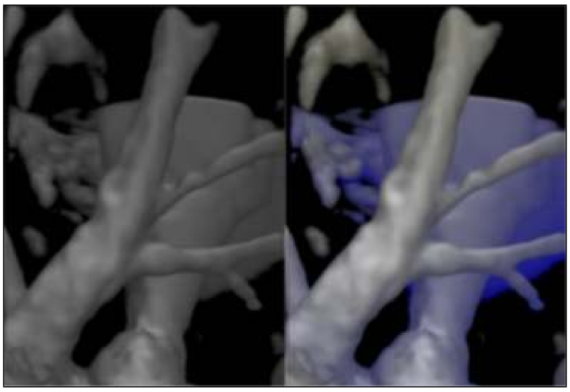

Figure 12: *Vascular structure visualization (from [JQD*08], © IEEE, reprinted with permission).* ***Left:*** *Conventional shading.* ***Right:*** *Distance color coding (more distant regions appear blue).*

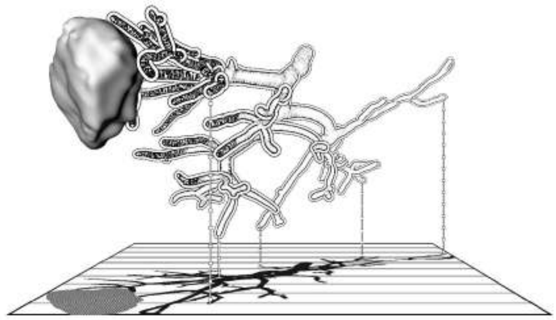

Figure 14: *Illustrative visualization of hepatic vasculature and a tumor. Supporting lines connect the 3D visualization with the ground plane to which the shadow is projected. Vascular structures in the safety margin around the tumor are emphasized with different hatching styles and a gray tone (Courtesy of Kai Lawonn, University of Koblenz-Landau).*

shadow generation technique that supports depth perception and that was shown to be effective for displaying complex anatomical shapes—the stripe texture is mapped to the occluded vessel close to the intersection in image space, resulting in the impression of a shadow. Thus, the authors refer to this technique as *depth-encoding shadows*. The distance is encoded twice: vessel branches that are far away in depth are indicated by smaller and darker stripes.

To indicate the different depth of branches of a vascular tree, another hatching technique is employed where, again, the distance is mapped to stroke density (see Fig. 13). Note that these mappings are not necessarily linear; the authors recommend an exponential function for better discrimination of different values.

Lawonn et al. [LLPH15] presented an illustrative visualization of vascular models that aimed at improving the depth perception. They combined supportive lines—inspired by methods from computer games [GCA*09]—with illustrative shadows and hatching based on different line styles to encode distances. This work is also driven by the needs of surgical planning and intra-operative guidance. Fig. 14 shows a realistic vessel tree derived from clinical CT data.

3.2.2. Chromadepth-Based Techniques

In Sect. 3.1.2 we introduced chromadepth as a perceptually-motivated color scale which can enhance the depth perception. This technique is particularly useful for the visualization of complex vascular trees. A vessel visualization with standard volume rendering and chromadepth coloring is shown in Fig. 15. Ropinski and colleagues have proposed a simplified chromadepth technique, which they refer to as *pseudo-chromadepth* [RSH06], in which only one transition color (purple) is used to blend between the proximal and distal parts. They have found that this technique provides an as much perceptual benefit as traditional chromadepth techniques. It has also been picked up by other authors [KOCC14] and used in combination with color, depth of field, and contours. A similar set of techniques is described by Chu and colleagues in the context of vessel visualization [CCG*08]. Joshi and colleagues additionally use toon shading and employ halos to support the depth perception [JQD*08]. Furthermore, they have applied an advanced vesselness filter and combined the resulting data with these conventional depth and shape cues.

Depth-Enhanced MIP. The widespread Maximum Intensity Projection (MIP) assumes that the structures with the highest intensities (those with a high uptake of a tracer or contrast agent in nuclear medicine or radiology) are the most important structures. Since the position of the maximum has no influence on the gray value, the depth perception is strongly limited. In particular, MIP images do not depict recognizable occlusions. Several attempts have thus

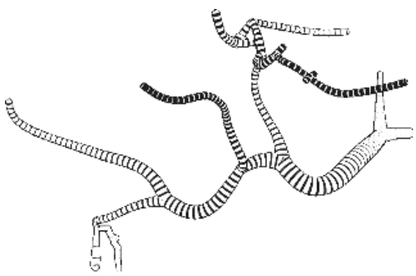

Figure 13: *The stroke density along the vascular tree shows the distance to the viewer. This black and white illustration may be printed and used for orientation in surgery (from [RHP*06], © IEEE, reprinted with permission).*

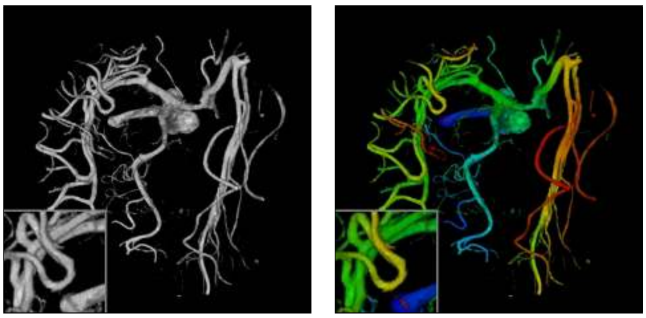

Figure 15: ***Left:*** *Standard direct volume rendering of a vessel tree.* ***Right:*** *Chromadepth coloring of the same data set supports the depth perception process by exploiting hue-based distance perception (from [RSH06], © Springer, reprinted with permission).*

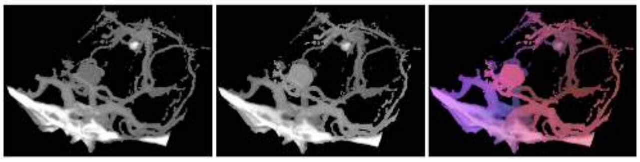

Figure 16: ***Left:*** *normal MIP rendering of cerebral vasculature with an aneurysm.* ***Middle:*** *depth-enhanced MIP.* ***Right:*** *depth-enhanced MIP with a pseudo-chroma color scale (Courtesy of Jose Diaz, UBC Barcelona).*

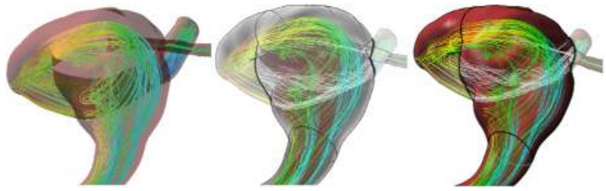

Figure 17: *A portion of a cerebral artery with an aneurysm is shown along with the internal flow. The left image was created with global transparency for the artery. The middle and right images were created as ghosted views, whereas the right image incorporates additional depth enhancement. The black lines in the middle and right image are results of a geometric analysis and indicate the inflow and outflow of the aneurysm (from [GNKP10]).*

been made to improve the depth perception in MIP images. From a perceptual point of view, the most important contribution is a chroma-based technique from Diaz and colleagues [DV10]. In addition to the MIP image, they create a depth map to detect whether the same material that lead to the maximum occurs at the same viewing ray again (a threshold slightly below the MIP intensity is employed). For pixels, where no occlusion occurs, the MIP information is used only to determine the gray value. In case of occlusions, the resulting gray value is determined based on a weighted combination of the maximum's intensity value and the depth. This depth-weighting is an adjustable parameter (i. e., the classical MIP may also be generated).

While this clearly enhances the depth perception (Fig. 16, middle), it is not ideal since luminance encodes intensity *and* depth. Therefore, Diaz and colleagues investigated whether the separate use of gray values (for intensity) and color (for depth) further improves perception. They investigated different color scales, including pseudo-chromadepth colors [RSH06] (Fig. 16, right). The evaluation with a number of depth perception tasks revealed that the majority of 12 participants performed much better with the depth-enhanced MIP and in particular with the additional use of pseudo-chromadepth colors. Performance was measured by comparing wrong, correct and "do not know" answers. Thus, the natural choice of red for the foreground and blue for distant regions was successful.

Due to the importance of MIP, other modifications were suggested that aim at improved perception. Most notably, Bruckner and Groeller [BG09] introduced the *Maximum Intensity Difference Accumulation*. With this technique, high opacity values are assigned to voxels with a strong gradient magnitude, thus emphasizing intensity differences as they occur at material transitions.

3.3. Blood Flow Visualization

For any kind of blood flow visualization, measured or simulated, it is essential that the patterns of the flow can be studied along with the morphology of the surrounding vessels. Changes, such as narrowings or dilatations of vascular structures, cause vortices or helical flow patterns. These subtle changes may be true representations of the patients' state, but they might be due to artifacts. Three dimensional flow is often represented with streamlines (which may be illuminated) or pathlines in case of unsteady blood flow (see [VPvP*14] for a survey). Color is used to convey the velocity magnitude and thus cannot be used to enhance the shape and depth perception (e. g.with toon shading or distance color-blending.)

Due to the complexity of the underlying information, perceptually-motivated blood flow visualization techniques primarily employ *illustrative* concepts. The simultaneous visualization of vascular structures and embedded flow is an instance of a multi-layered visualization, similar to the display of an organ surface and internal structures. Therefore, one may consider using sparse line drawings to represent the outer surface [IFP95]. However, showing an outer surface with feature lines and the flow with streamlines would lead to a clutter of line-based visualizations. Thus, alternative representations for the outer surface are required. Specifically, showing the flow inside a vascular structure requires the vessel ton be rendered transparently. There are different variants for the use of transparency. A global adjustment for the whole vessel is the simplest method. Opacity maps (e. g., with stripes being more transparent) are also possible [BH07].

Ghosted views. Ghosted views are a type of smart visibility technique. Often, the region, where real flow is represented, would define a 3D mesh (e. g., a hull), and the transparency of the vessel is adjusted such that the flow becomes visible. Regions of the vessel surface that do not occlude flow are rendered opaque. Gasteiger and colleagues [GNKP10] developed such a ghosted view technique, where the transparency is adjusted in a view-dependent manner so that vessel contours are clearly visible.

Ghosted views can also be combined with feature lines that indicate, where a pathology starts and which vessels drain and feed the pathologic dilatation. Moreover, an optional depth enhancement has been introduced with a fog simulation and a simple approximate shadow representation. This gives rise to possible visualizations: simple global transparency adjustment, ghosting, and ghosting with additional depth enhancements (see Fig. 17). While Gasteiger and colleagues [GNKP10] only assessed the subjective preference of the techniques, a full perception-based study of this technique has been performed [BGCP11] and will be described in Sect. 5.3. The combination of blood flow and vascular structures was later refined and adapted to animating time-dependent flow [LGP14].

Illustrative techniques were developed to provide simplified abstract flow representations [BMGS13, vPBB*10], motivated by artist-created flow illustrations. Occluding contours emphasize major arteries and their branchings if drawn over a strongly transparent surface. Illustrative *arrow glyphs* were employed to display aggregated flow (using clustering). Long arrow glyphs are beneficial for the perception of the flow direction [War08].

3.4. Fiber Tract Visualization

Several attempts have been made to present brain white matter or muscle tissue fiber tracts such that the depth perception is well supported [Ise15]. Generally, two major approaches are used: traditional illumination for tubular primitives or purely line-based techniques.

3.4.1. Projection and Illumination of Stream Tubes

Weigle and Banks [WB08] created artificial datasets resembling fiber tracts visualized with stream tubes. To investigate shape perception (local scale), they modified the perspective (orthographic and perspective) and the illumination model (local and global), the latter having been introduced by Beason and Banks [BB06]. The illumination model includes shadow generation and multiple reflections that can be precomputed and thus be used in interactive settings. To fully exploit the perceptual potential of global illumination, several light sources need to be placed carefully (serving as key lights and fill lights). Overall, they found that global illumination and perspective projection improved the assessment of depth with highly significant results and a moderate effect size. Global illumination improved the depth perception in case of orthographic and perspective projection. Thus, the effects of realistic perspective and illumination are cumulative.

In addition to, or instead of, using (local) illumination of the tubular fiber tract structures, researchers have also investigated the use of graphical techniques (i. e., illustrative visualization techniques) that have an effect similar to global illumination (recall Sect. 3.1.1), but which can be more computed rapidly. In particular, Wenger and colleagues [WKZL04] employed *tube halos* and motivated the use of halos with their improvement of perception, as shown in the previously mentioned work on flow visualization [IG97]. Generally, this use of similar visualization approaches illustrates the close connection of fiber tract visualization to that of other types of dense line data (e. g., streamlines) extracted from flow simulations. As an alternative, Klein and colleagues [KRH*06] removed tube shading entirely and, instead, applied distance-encoded contours and tube shadows to improve the spatial perception—freeing up the tube surface for the visualization of additional data properties. No studies have been conducted to evaluate the perceptual benefits of the either of these visualization techniques.

3.4.2. Line-Based Visualization

While tube-based fiber tract visualizations support spatial perception through the (locally or globally computed) shading applied to the primitives, this approach also requires a considerable amount of screen space per tract to work effectively. To cope with the generally dense character of the fiber tracts extracted from brain or muscle datasets (or lines extracted from flow data, such as in hemodynamic simulations [LGV*16]), researchers have also explored approaches that rely on lines as the major rendering primitive to display more fiber tracts in a visualization. For such visualizations, approaches similar to those used for tube-based representations are used to enhance the spatial perception of the 3D structures.

The analog of illuminated tubes is the use of *illuminated lines*, a physics-based visualization technique. Several groups [CYZ*09, PVStHR06, ZB03] use this technique to illustrate fiber tracts extracted from muscle tissue data. As line illumination (e. g., using a Phong illumination model adjusted to lines) only carries local information, Peeters and colleagues [PVStHR06] add *line shadows* using high-resolution shadow maps. This nor only improving spatial perception, it also improved the coherency of the data since shadowed lines indicate fiber occlusions more clearly than illuminated lines alone.

An alternative to computing line shadows is the use of illustrative

Figure 18: *Depth-dependent halos [EBRI09] applied to a selection of white matter fiber tracts in the brain.*

line halos which are similarly able to indicate occlusions and, thus, improve the perception of the spatial arrangement of dense fiber-tract structures. Like some methods for tube-based representations, Everts and colleagues re-interpreted the line representations as line strips [EBRI09, SEI10, EBRI11, EBRI15] to add halos around each fiber tract. These halos, however, only occlude other lines if the distance is greater than a given threshold. This *depth-dependent halo* ensures that fiber tract bundles *visually* appear as such, only occluding other fiber tracts further away (see Fig. 18). Similar to Klein et al.'s [KRH*06] approach for stream tubes, depth-dependent halos facilitate the encoding of additional data in the lines by using special line primitives [EBRI11, EBRI15, LGV*16]. While the depth-dependent halo technique was only informally evaluated with neurologists, those experts claimed that the technique "better shows depth relation and structure" and that tract bundles are well emphasized.

Although realistic global illumination is clearly the best rendering approach for supporting the perception of 3D structure, it is is expensive to compute. Less computationally expensive approximations of it are viable alternatives, such as focusing on the important features it adds, of which shadows and halos are only two. On such alternative is the physics-based technique of *ambient occlusion*, which has been used for fiber tract visualizations. The first to explore the use of ambient occlusion for fiber tract visualization were Díaz-García and Vázquez [DGV12] and Hermosilla and colleagues [HBVV12]. Both approaches focused on small fiber tract selections and used screen-space ambient occlusion (SSAO) due to its fast performance.

All line-based approaches discussed so far, however, only work well for sparse datasets or selections of fiber tracts in which tract bundles are clearly emerging. Otherwise, the dense nature of fiber tract data coupled with unstructured fiber tract orientations toward the outside of a dataset (at least for brain data) make it difficult to perceive the overall 3D structure. Eichelbaum and colleagues [EHS13] thus developed **LineAO** (Fig. 19), a physics-based technique that specifically supports the perception of complex 3D structures in dense fiber tract datasets. Eichelbaum and colleagues claim that the sampling of dense linear structures can handle both the global structure and the local detail. Moreover, the technique can also be combined with line illumination and the visualization of additional data properties along the tracts. LineAO's primary limitation is that it is not so well suited for use with sparse data due to its lack of occlusion [EHS13].

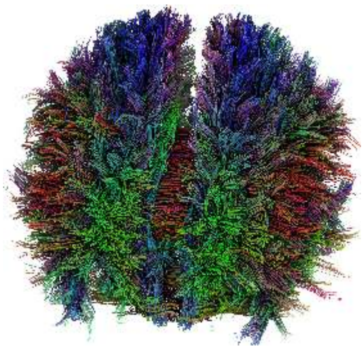

Figure 19: *LineAO [EHS13] applied to white matter fiber tracts extracted from a whole-brain HARDI dataset.*

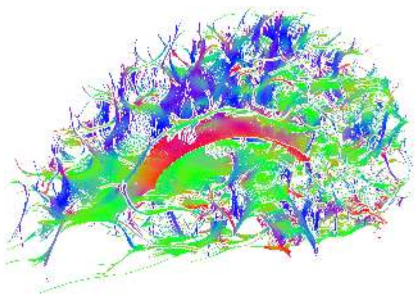

Figure 20: *Fiber tract contraction [EBB*15] to support the perception of higher-level structures.*

3.4.3. Abstraction for Perception of Global Structure

While most perceptually-motivated visualization techniques for medical data are restricted to changes of the depiction of elements, fiber tract data is an example that one can also improve the perception of structures at higher levels of scale by changing the geometry of the underlying data. In the case of fiber tracts, this can be done though tract contraction, whereby individual tracts are locally relocated to emphasize the structure of the overall bundle. This approach was demonstrated by Everts and colleagues [EBB*15] and can be combined with other techniques, such as depth-dependent halos (see Fig. 20).

4. Perceptual Experiment Methods for 3D Visualization

This section provides a compact discussion of essential aspects of perceptual experiment methods and serves as the basis for assessing experiments to be discussed in Sect. 5. It provides hints about how the shape and depth perception can be empirically assessed. Although medical examples are used, this discussion is more general than the remainder of the STAR.

An experiment can be thought of as a systematic testing of something under rigorously controlled conditions in order to answer a question. A basic knowledge of experimental design can lead to deeper insights into the advantages and disadvantages of certain 3D visualization techniques. A more detailed discussion of experimental design and its use in computer science can be found in [CW11].†

4.1. Terminology and Fundamental Concepts

A *stimulus* is shown under controlled *presentation conditions* to *participants* who are asked to perform some *task*. In a perceptual experiment studying medical visualization, the stimuli are generally images or videos generated either with different visualization techniques or with different parameter values for a single technique. An *independent variable* characterizes the thing that has to be studied and that is thus systematically varied when generating the stimuli. Each independent variable is called a *factor*. The different values of each factor that are (systematically) chosen are called *levels*. The experimenter may manipulate more than one factor. The complete combination of factors and levels for any single trial is a *condition*. For instance, a two-factor experiment (e. g., emphasis technique and monitor type) might have three levels of the first factor (ghosting, spot light effect, and color modification) and two of the second (2D vs. 3D), yielding a 3×2 experiment with a total of six conditions. A *dependent variable* measures an aspect of the participant's behavior that should be affected by the independent variable.

Two forms of experimentation exist. In an *observational study*, the experimenter waits until the desired event or situation arises spontaneously. An *experimental study*, or controlled study, relies on events or actions that are intentionally caused by the experimenter.

Quantitative measurements provide numerical values, which may be ordinal or interval. These measurements are usually subjected to statistical analysis (see Sect. 4.4). *Qualitative measurements* provide nominal data and are almost always verbal reports. To allow a statistical analysis of qualitative data, the verbal reports must be preprocessed such as by categorizing or cataloging them. This provides, for example, the frequency of certain types of answer. Qualitative measurements are often used at the initial stages of a line of research.

Thinking is not the same as doing. Amazingly often, experiments merely ask people what they *think* they would do or would choose in a given circumstance, and as such is a *meta-cognition* task (or simply meta-task). Meta-tasks tend to be qualitative, but can be quantitative. For example, an experimenter could present a number of medical visualizations and ask the participant which version they think is best at communicating the shape of the structures. The participant is essentially saying "if I had to actually measure the shape, I think I would perform better in this condition." A *direct task* asks the participant to actually perform the desired action. Note that some tasks, such as rating scales and forced choice, are clearly quantitative, but can be used either as a meta-task or as a direct task. It has repeatedly been shown that people are not always able to predict their own behavior. Thus, meta-task results often do not accurately predict the related direct-task results.

We focus on experimental studies using quantitative measurements (both meta and direct). Psychophysical experiments receive a special emphasis. Psychophysics [Fec60] is a branch of experimental psychology that exerts extremely rigorous control over all aspects of an experiment in order to be able to infer something about the underlying perceptual processes from a participant's behavior [CW11]. In particular, it can isolate the parameter or independent variable that caused the measured change in behavior.

† See http://psychtoolbox.org/ for a Matlab-based tool to support psychophysical experiments.

4.2. General Considerations

Here, we discuss a few general issues related to designing and understanding an experiment.

4.2.1. Research Question versus Hypothesis

Each experiment attempts to answer a *research question*. The more concrete and explicit this question is formulated, the more obvious it will be what needs to be done to answer the question. Moreover, a complete and explicit question helps to avoid potential biases and confounds. A research question is different than a hypothesis. A hypothesis is a formal statement of the expected result. For example, one might hypothesize that participants will be faster and more accurate with a certain visualization technique than with others, or that technique A will be preferred over technique B. Many statistical procedures explicitly require a “Null” hypothesis, which is a logical negation of the hypothesis. The Null hypothesis effectively states that “the experimental manipulation will have no measurable effect on this task to an infinite number of decimal places”. It is often believed that the Null hypothesis can never—even in principle—be true [Lof91]. As such, the use of Null-hypothesis-based statistical analyses is under debate in Psychology, HCI, and visualization [Dra15, Lof91, IIC*13].

4.2.2. Specificity versus Generality

An experimenter can make *definitive* claims only about the specific situations that were actually measured. Measuring every possible level of every factor is, however, not practical. Fortunately, as long as a few simple rules are obeyed, it is possible to confidently generalize beyond what was actually measured to other, similar conditions. These rules become obvious if experimentation is viewed as sampling an unknown function.

Imagine that we could input some values into an unknown function and receive the output at that point without having any knowledge of the function (sometimes this is called using an oracle). It would be possible to fully characterize the unknown function by measuring the output for all possible inputs. If only a few points that are near to each other were measured, it would be possible to speculate about the value of the neighboring, non-measured points—for example, using linear interpolation. This assumes that the function is analytic and at least locally close to being linear. Naturally, interpolation or generalization involves some uncertainty. An experiment does the same thing, using the participants as oracles. Thus, by generating the stimuli by systematically sampling along a single dimension, we can make clear, reliable claims about both the measured points and the intervening points.

4.2.3. Methodological Considerations

A few issues need to be addressed for all experiments.

Variability and Repeated Measures. There is an inherent, unintended variation in human behavior (see, e. g., [BSO*87]). This means that no behavioral measurement will be very precise, no matter how good the equipment is. Since this variation will be different every time we measure the target behavior and is generally normally distributed, it can be treated as a noise term. If performance on a given task is repeatedly measured, the average of those measurements will be (more or less) devoid of noise.

Confounds. Any average difference in *performance* between the conditions of an experiment will result from one or more *design* differences between the two conditions, whether those design differences were intended or not. For example, if an experiment were to intentionally vary visualization techniques but did not use the same dataset for all techniques (e. g., it used anatomical models for one technique and machine parts for the other), then performance differences might be due to the visualization technique or the nature of the dataset. The participants and the datasets may not represent the whole population or the whole variety of possible datasets well. As an example, datasets from (young) healthy volunteers may be easy to acquire, but they do not represent pathological variations in clinical data (this is called a *sampling bias*). If a task is to be performed with different visualization techniques, the order in which the visualization techniques are employed matters due to a learning effect. That is, participants will be faster and more accurate with the last technique, even if it is not better than others. These and other unintended changes are potential *confounds*. Thus, all conditions of an experiment need to be as similar as possible to be able to isolate the variable(s) that caused changes in the dependent variable(s).

Selection of Participants. Participants should represent the target user group. Thus, if complex surgical procedures should be supported, medical experts with this specialty are required. Medical visualization techniques for educational purposes should be tested with students of medicine. Unfortunately, the recruitment of a sufficient number of medical experts is often simply not possible. One alternative is to simplify the task or use a different but related task that can be accomplished by knowledgeable students of other disciplines. This strategy, however, clearly endangers the *external validity* of a study (i. e., the possibility to transfer the results to the real world). Every experiment should record and report the age of the participants, the background experience or expertise of each participant with the current task and stimuli, and the number of males versus females in the group.

Within- and Between-Participant Designs. Averaging the scores of different people will remove any variation in performance caused by individual differences. A *Between-Participant* design uses a different group of people in each condition. Although this ensures that performance in each condition is independent, it adds a potential confound: performance differences might be due to people in the different conditions. As the number of participants increases, the likelihood of this confound decreases. This confound can be avoided by having each person participate in all conditions. This is called a *Within-Participant* design and is the standard in perceptual experiments. While this has many advantages, the downside is that performance in the different conditions is no longer really independent. What participants see or do in any given condition may affect how they perform in subsequent conditions. The most common solution to avoid this confound is to randomize the presentation order: each participant sees every condition, but in a different, randomly chosen order. This converts order into a noise term, which can be eliminated by average performance.

4.3. Selection of Tasks

The task should be representative of the real-world scenario that underlies the research. For example, a medical visualization system that primarily serves educational purposes, such as a surgery simulator, would call for a basic manipulation task in a minimally invasive training system. A therapy planning system, on the other hand, focuses on decision-making (e. g., if surgery is possible or whether a radical or a gentle surgical strategy is appropriate) and would require a different task. Although it is difficult to relate the

Table 1: *Quantitative methods yielding objective data.*

Task	Measures	Example
Depth judgment	relative depth ordering of a set of points (often a pair)	This task is often used to asses the spatial relations of complex anatomical structures, such as a pathology among vessel trees. Here, a number of concrete locations in the image are marked and participants need to indicate which is closest, second closest, etc.
Relative depth	relative depth separation of pairs of points	This task measures depth intervals. For example, two pairs of points (p_1, p_2) and (p_3, p_4) are presented and participants must indicate which pair is closer to each other.
Depth profile	either accuracy in localizing depth-based minima and maxima or accuracy of a participant-drawn depth profile	In this task, participants are shown a 2D view of a 3D object and a line or set of points is placed on top of a part of the model (see Fig. 21). Participants are asked to estimate the depth profile along that line, for example using an orthogonal view of the line.
Orientation matching	participants' ability to manipulate a 3D probe to match local surface orientation	This task is often used to measure how well people can perceive local surface orientation and generally uses a gauge figure as a probe, for example to assess the display of pathologic structures, where shape details may indicate the benign or malignant character of a pathology. This is a tricky task to use and has a long history. See the text below for more information.
Orientation discrimination	estimates of the ability to discriminate aspects of local surface orientation	This task presents one or more surfaces and a list of possibilities (e. g., convex versus concave). The participant must choose one answer to describe the image (i. e., a forced choice task). By systematically varying the desired surface aspect over stimuli, it is possible to find, for example, the smallest degree of convexity that is perceivable, or which techniques allow for better perception of curvature.
Surface categorization	participants' ability to determine qualitative aspects of an object	In this task, objects are presented that have different values for some surface type category, such as geometric form (e. g., elliptical, cylindrical, saddle type, or flat) and participants need to categorize the different 3D objects. This often uses a forced choice task and is similar to orientation discrimination.
Structure recognition assessment	assesses for a set of images (often a pair) generated with different rendering parameters the recognizebility of details	often used to understand the effects of different lighting configurations (number of light sources, light source placement, illumination model)
Object placement	speed and accuracy of interaction with 3D objects	This task asks participants to manipulate a 3D object, often to place it on another 3D object. For example, it is often used to study whether implants, stents, or similar tools are conveniently and correctly selected to fit to the anatomy of the particular patient.

speed and accuracy with which people complete the experimental task to specific differences in medical visualization techniques, these notions are the ultimate measures for success.

4.3.1. Common Direct Tasks

In addition to actual manipulation tasks, common tasks include some form of verbal report, a forced choice among a short list of items, or a rating along a fixed scale (such as a Likert scale). Rating is usually done on a Likert scale, which uses (mostly) an odd number of possibilities (5, 7, or 9) and anchors the two ends of the scale, usually with opposing terms. The most common Likert scale is a 7-point scale with 1 meaning "strongly agree" and 7 meaning "strongly disagree". Typical quantitative tasks from perception research may be adapted to medical applications. Table 1 summarizes important tasks and specific measures with a focus on the shape and depth perception.

Orientation Matching Tasks are rather complex, and require a more detailed discussion. The most common orientation matching task asks participants to place *gauge figures* (disks centered around an orthogonal line) at selected positions of a surface. Participants are asked to manipulate the orientation of each gauge figure so that its base plane is tangent to the surface and thus the orthogonal lines match to the normal vector at that point of the surface. The curved surface is thus *probed* at different positions.

Gauge figure tasks were pioneered by Stevens [Ste83] and are widely used to assess the influence of visualization techniques on the shape perception (e. g., [BGCP11,CSD*09,KVDK92,SPV11]). Cole and colleagues [CSD*09], for example, used a repeated measures shape task to determine which technique provided better shape perception as well as to measure how certain the participants were. Cole and colleagues also pioneered *gauge string tasks*, where a number of gauges (15 in their case) were placed on a horizontal line to analyze shape perception in a local region in-depth and to correlate the results with differential geometric properties, such as the occurrence of inflection points.

Placing gauge figures is not easy, in particular because the gauge occludes parts of the surface. O'Shea and colleagues [OBA08] have discussed guidelines for gauge figure tasks, suggesting that gauge figures should be

- drawn in red,
- drawn with a small line width to reduce occlusions,
- initially oriented randomly, and
- shown in perspective projection.

Moreover, it is useful to present the gauge figure in its current orientation enlarged at the boundary of the image (where the currently interesting part of the surface is not occluded) [SW04]. It is also important that the gauge figure does not interact with the surface (including occlusion effects!), since this would give direct feedback as to the correct location of the surface. Participants need to practice placing gauge figures and should be shown correct and bad placements [CSD*09].

4.3.2. Preference-Based Evaluation

The simplest and thus most widespread approach to comparing medical visualization techniques is to ask participants about their preferences. This a typical add-on for a paper that introduces a new

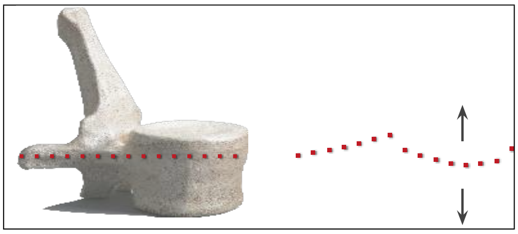

Figure 21: *Depth profile task: A complex shape with concave and convex regions. A profile line is given (left) and participants should assess the corresponding depth values. With Phong shading, participants often precisely locate minima and maxima, but they underestimate the differences in depth considerably. (Spine image from: https://www.flickr.com/photos/64219942@N02/6340826370/in/album-72157627892068346/, License CC BY-NC 2.0, https://creativecommons.org/licenses/by/2.0/).*

Figure 22: *A variety of visualizations (with identical viewing parameters) of liver anatomy, differing in the use of colors and rendering techniques. In pairwise comparisons the combination of shaded surfaces and black and white silhouettes was identified as the preferred style (from [TIP05]).*

method and is meant to convince the reviewers that the new method is better than previous methods. Tietjen and colleagues [TIP05] for example compared visualizations of liver anatomy aiming for improved shape perception with feature lines (see Fig. 22). They found systematic differences in the preferences of laypersons and surgeons for different types of structures. As mentioned previously, however, an aesthetic preference for a technique does not necessarily mean that this technique will in fact produce faster or more accurate results when used in a quantitative task, let alone in the real-world setting [BCFW08]. Preference-based evaluations involve meta-cognition and are very subjective [IIC*13]. Thus, they generally do not support precise claims and the results are often difficult to integrate with perceptual theory.

4.3.3. Eye Tracking-Based Research

The use of eye tracking has become quite popular for evaluating user interfaces, web sites, and 2D visualizations [BE14]. Modern eye trackers can deliver precise and reliable results about *foveatic vision* (i. e., the regions of a 2D image observed in high resolution). Eye motion evaluation focuses on scan paths and fixation regions in 2D screen coordinates. The disadvantages of eye tracking include that eye movements are often unintentional, that we may fail to recognize an object even if we have looked at it for long time, and that eye motion is only weakly correlated with cognitive processes. Eye motion also does not indicate at which distance (e. g., which layer of a semitransparent 3D model) a person is focusing. Furthermore, peripheral vision cannot be detected with eye tracking [KDX*12].

Eye tracking has been used in the visualization of medical image data, in particular to analyze how physicians inspect X-ray images in, for example, mammography data (see, e. g., [BHKS13, Kru00]). With respect to 3D medical visualization, Burgert and colleagues [BOJ*07] investigated 3D renderings of the neck anatomy with enlarged lymph nodes. Experienced participants had significantly less saccadic movements and looked longer at the relevant regions while novices tend to look around more. Eye tracking has been used to automatically adjust parameters for volume rendering to highlight regions of interest, determined by means of eye tracking [LME10]. The central and by far most reliable result, however, is that novices and experts have different eye-motion behavior. In a meta-study of eye motion when looking at visualizations, Gegenfurtner and colleagues [GLS11] found that when a large enough number of participants is used, experts show shorter fixation durations and have longer saccades. They also have more fixations in the relevant areas and take less time before the first fixation on relevant information. This is the same pattern found in many non-medical tasks, such as chess or driving [BYW*11], and seems to reflect the degree of expertise in the relevant task. Lu and colleagues [LME10] provide a comprehensive overview of eye tracking-based research in visualization.

4.4. Statistical Evaluation

Here, we focus on a few core aspects of data analysis.

Descriptive statistics summarize the measurements [CW11]. The most common descriptive statistics involve measuring the central tendency (e. g., mean, median, and mode) and the variation (e. g., standard deviation). Note that the mean and the standard deviation represent the first two statistical moments [PCR13] and are very useful for characterizing data that follow a normal distribution. Often, the results do not follow a normal distribution, in which case the range, the interquartiles and the median are more useful, as are the higher statistical moments. The third and fourth statistical moments correspond roughly to the skew (a measure of asymmetry in the distribution) and kurtosis (essentially how much of the distribution is concentrated at the mean, and as such related to sparseness).

Inferential statistics seek to make inferences about a larger population and as such they try to make claims beyond the measured data based on statistical assumptions [CW11]. Often, these tests involve comparing the test's results with what one would expect if the data in the conditions were in fact sampled from the same underlying population (i. e., if the manipulation has no effect), which implicitly applies the Null hypothesis. Given the problems with Null hypothesis testing, it is highly advisable to assess the *effect size*—a measure that defines *how* different two distributions are [Coe02]. For normally distributed data, the effect size relates the difference between mean values to the combined standard deviation. An effect size of 0.2 is small, 0.5 is a moderate effect size, and anything above 0.8 is considered to be a large effect size. If a simple technique is compared with an advanced and expensive technique, effect sizes are crucial to understand whether the advanced technique is not only better but whether the additional effort is justified.

5. Evaluation of Perceptually Motivated Visualizations

In this section, we come back to the perceptually motivated medical visualization techniques and describe selected evaluations that were performed to investigate their effectiveness. While we searched for evaluations related to all categories of medical visualization techniques discussed in Sect. 3, we found no comprehensive evaluation of fiber tract visualizations. We did find many evaluations related to vessel visualizations [BGP*11, JQD*08, KOCC14, LLPH15, RHP*06, RSH06]. As comprehensive evaluations of volume rendering techniques, we identified the following papers: [CRD10, DRN*16, GSBH13, LR11, SPV11, ZCBM14]. For blood flow visualization, we identified only the study of Baer and colleagues [BGCP11]. We discuss a subset of the above-mentioned publications using the following structure:

- type of evaluation (e. g., qualitative or quantitative, within or between participants),
- setting of the evaluation (e. g., local or remote web-based),
- participants (e. g., number, portion of females and physicians),
- tasks, and
- major results.

Some techniques were evaluated with different methods (e. g., related to shape and depth perception). Therefore, for some techniques, several evaluations are described according to the template discussed above. All evaluations are based on explicit hypotheses, as discussed in Sect. 4.2.1. For the sake of brevity, the hypothesis are not mentioned in the following descriptions.

5.1. Evaluation of Volume Visualization

In the following, we describe the evaluation of two illustrative volume rendering techniques.

5.1.1. Enhanced Two-Level Volume Rendering

In Sect. 3.1.2, we described perceptual enhancements of volume rendering based on two-level volume rendering [CRD10]. These enhancements were the subject of a quantitative evaluation related to shape perception that was performed as a gauge figure task.

Type of evaluation: quantitative, between-participant design

Participants: 14 (4 females), all participants were familiar with computer graphics and thus with surface normals.

Environment: Each participant downloaded the application and performed the experiment on his or her computer. Thus, there was no control over the display.

Stimuli: Three medical CT and MRI datasets were used (skull, bone, brain). The data were rotated between the experiments to avoid any learning effects. Each dataset was shown eight times with different gauge positions.

Factor and levels: Lines were extracted from the volume data with different techniques. Besides silhouettes and suggestive contours, the results of edge detection filters (Sobel, Canny detector, Difference of Gaussians) were employed. Different combinations of these lines were considered. Color saturation was an alternative emphasis technique. As a result, 15 levels were investigated (no stylization compared to 14 single or combined line drawings).

Tasks: Orientation estimation with gauge figures.

Major results: The lowest angular deviation (about 32 degrees) was achieved with the isolated use of canny edge detection, difference of Gaussians and Suggestive Contours. The isolated use of silhouettes was only slightly worse. This was a significant improvement over no stylization (deviation: 36 degrees). With most combinations of lines, participants performed worse than with no stylization at all.

The participants benefited much more from stylization with the brain model. The authors speculate that the participants are more familiar with the shape of the head and foot. Thus, experiments like this should explicitly analyze whether the choice of the datasets influence the accuracy of user ratings.

5.1.2. Chromadepth Shadows

In Sect. 3.2.2, we described chromadepth shadows as a technique that incorporates shadows as depth cue, where the *shadowiness* was mapped to color. Thus, a color contrast in darkened areas arises [SPV11]. The authors conducted three evaluations to assess the perceptual consequences of their work. The experiments relate to shape perception, depth perception, and contrast perception. We discuss the first two experiments.

For shape perception, an orientation matching task was performed. The placement of the gauge figures was selected such that different colors occurred in these regions. The angular deviation was estimated at these positions and related to the color.

Type of evaluation: quantitative, within-participant design

Participants: 8 (no physicians, no females), all familiar with computer graphics

Environment: One monitor was used for all experiments. It was calibrated and constant lighting was ensured.

Stimuli: artificial, sinusoidal waves with 175-211 tests for each shadow color, resulting in 1005 samples in total

Tasks: orientation estimation with gauge figures

Major results: The angular deviation was computed for five shadow colors (mean, standard deviation). Mean values ranged from 32 to 39 degrees, the highest deviation being observed for the darkest color. A small trend towards better shape perception in brighter areas was found.

Further remarks: This was a small study without any advanced statistics. No significance or effect sizes were reported.

Depth Perception with Chromatic Shadows. The depth perception experiment from [SPV11] served to compare three lighting conditions in their effect on depth judgment.

Type of evaluation: quantitative, within-participant design

Participants: 63 (a few physicians, 8 females), 50 participants were familiar with computer graphics

Environment: Each participant downloaded the application and performed the experiment on his or her computer.

Stimuli: cardiac ultrasound data, four scenes, 506 test stimuli

Factor and levels: The lighting condition was varied using three levels: Phong shading (no shadows), conventional soft shadows with darkening, and chromadepth shadow

Tasks: Depth judgment task. Two points were presented on the surface. These are at distance 0 and distance 10. A third point was then presented (with a different color) and the participants were to estimate its relative depth value.

Major results: Results were shown in a diagram that contained the median, inter-quartile range, and range for the three levels of lighting. No precise numbers were given. The inter-quartile ranges of Phong shading were completely outside those of the two shadowing variants. Obviously, the two shadowing variants were significantly better with at least a moderate effect size. The difference between the two shadowing variants was small and clearly not significant. There was a slight tendency for the depth perception to be more accurate with the conventional shadowing algorithm.

Further remarks: No numbers were given and no statistics were performed. Since the majority of the participants were familiar with computer graphics (Phong shading, traditional shading) the new chromadepth shadowing might have a disadvantage. In essence, no definitive statement about a perceptual advantage of chromadepth shadows is possible.

5.2. Evaluation of Vessel Visualization Techniques

We described a number of vessel visualization techniques in Sect. 3.2. The depth-enhanced techniques introduced by Ritter and colleagues [RHP*06] were evaluated in experiments performed as a web-based study. Thus, display conditions and illumination were not controlled. Even the selection of participants was not under complete control. Nonetheless, a large number of participants were used, which should average out some of the noise. The evaluation had different parts, including questions related to the personal preference of the newly developed compared to conventional visualization techniques. The quantitative experiments served to assess depth judgment and distance estimation. Table 2 summarizes the evaluations described in this section as well as a few other comprehensive evaluations.

Type of evaluation: quantitative, within-participant design

Participants: 160, among them 38 medical students or physicians, 77 females (age range: 17 to 56 years)

Environment: Each participant answered a questionnaire with a set of prepared visualizations via a web browser.

Stimuli: Vascular surface models. For pairwise comparison, the models were strongly rotated after the user answered a question with the first visualization technique. Since people cannot (easily or accurately) mentally rotate such complex models, learning effects are avoided.

Factor and levels: Illumination was studied with two levels (Gouraud shading and depth-encoding shadows) using a depth estimation task. Visualization technique was studied with two levels (Gouraud shading and depth-encoding texture, recall Fig. 13) using a depth judgment task.

Tasks: Participants were instructed to perform each step as quickly as possible.

Major results: Participants were faster and more precise in the distance estimation task with the depth-encoding texture. These effects were statistically significant. No effect size was given, but based on the mean and standard deviation it is approximately 1—a large effect size. Participants preferred a double encoding of depth by adapting the shadow's size and darkness (compared to only size and only darkness). The depth judgment task benefited from explicit distance encoding. Again, both the response time and the accuracy were significantly better. Although it would be interesting to analyze the physicians separately, this was not done.

5.3. Evaluation of Visualization Techniques to Show Blood Vessels with Internal Flow

In Sect. 3.3, we described techniques that display blood flow embedded in vascular structures. Among them were visualization techniques that adjust the transparency only in regions, where flow is present and employ further depth cues to assess the depth position of the flow [GNKP10]. We refer to the simple ghost view technique as G, to the method with further depth enhancement as GD and to the standard technique of global semi-transparency as S. A number of research questions arise that guide a perceptual evaluation:

- Is the shape of the vessel better recognizeable with G, GD or S?
- Is the internal flow better recognizeable with G, GD or S?

Baer and colleagues [BGCP11] experimentally addressed these questions. Their shape perception experiment was performed using a gauge task. It is important to mention that 3D rotation within certain limits is technically possible with these techniques and that such rotations make the task more realistic. Thus, In one group, participants were allowed to rotate the surface models by up to 15 degrees in all directions, effectively enabling motion parallax as depth cue. In the following, we discuss selected aspects of two experiments related to shape and depth perception (for more, see [BGCP11]).

5.3.1. Shape Perception Experiment

Type of evaluation: Quantitative, between-participant design.

Participants: Two groups with 17 participants each (no physicians, sixteen females—six in one group, ten in the second—aged 20 to 35), all familiar with computer graphics.

Environment: One monitor was used for all experiments. It was calibrated and constant lighting was ensured. To avoid influencing participants by different instructions, written instructions were provided. In the training trial, participants were given an unlimited amount of time in order to familiarize themselves with the stimuli and the gauge task. The stimuli used in the training trials were not shown in the following study.

Stimuli: Five cerebral aneurysms chosen from a large database to reflect different configurations (e. g., bifurcation aneurysms and "simple" dilatations as well as aneurysms of different size). Some aneurysms were presented from different viewpoints resulting in a total of nine different stimuli. The viewpoints were chosen together with neuroradiologists. The gauges were placed such that opaque, semitransparent and transparent regions were measured.

Task: Orientation estimation with gauge figures. To analyze the estimated surface normal, it was compared with the surface normals that participants gave with a fully opaque rendering of the Phong-shaded vascular surface (see Fig. 23). Thus, this opaque representation was considered as the Gold standard. The groups performed the tasks either with limited rotation enabled or disabled.

Major results: With rotation enabled, ghosted views (G) without depth enhancement significantly outperformed the two other techniques. As a side-effect, the perceptual consequences of enabling rotations were recorded. The average angular deviation was between 21° and 26° for the different stimuli when rotation was enabled and between 28° and 31° when rotation was disabled. This difference was statistically significant. When rotation was disabled, no visualization technique had a significant advantage over any other.

5.3.2. Depth Perception Experiment

The same environment as in the shape experiment was used.

Type of evaluation: Quantitative, within-participant design.

Figure 23: *The participants estimated the surface normal based on a fully opaque rendering of the vessel surface (right) and based on the three visualization techniques that convey the embedded blood flow. Ideally, the two normals would not differ and the internal flow could be presented without hampering surface assessment (from [BGCP11]).*

Participants: 25 (no physicians, 15 females, aged 18 to 30), all familiar with computer graphics

Stimuli: Four cerebral aneurysm models with internal blood flow, shown from three different viewing directions and with the same three visualization techniques (G, GD and S) resulting in 36 stimuli for each participant.

Tasks: Users were to assess the depth order of vascular branches (depth judgment task). Possible answers are: A is in front, B is in front, or both are at the same depth level.

Major results: Random guessing with three possible answers would yield correct answers 33% of the time. The actual results were that 45.0 %, 49.7 % and 50.4 % correct answers were given with S, G and GD, respectively. Both G and GD had a statistically significant advantage over S.

Further remarks: All participants were young computer graphics experts, not neuroradiologists (the target users). Blood flow visualizations, however, are not familiar to these target users so that experience has little influence on the perception of the visualizations and the results can probably be generalized to neuroradiologists.

5.3.3. Illustrative Visualization of Vascular Surfaces

Two evaluations were performed in order to assess the perceptual consequences of a new illustrative vascular visualization technique [LLPH15] (recall Sect. 3.2). The first qualitative study basically served as a pilot study to design a more thorough quantitative experiment.

Type of evaluation: Web-based questionnaire.

Participants: 50 (8 physicians, 19 females, 17–48 years of age). The largest group (24) were computer scientists.

Stimuli: 24 vascular trees along with a tumor with two selected and emphasized points. Participants had to assess their depth order. Static images were presented without a facility to change the viewpoint. In total, 1200 depth comparisons were evaluated.

Tasks: The participants saw vascular trees and a tumor as a typical situation in treatment planning. Two points were selected and the participants were asked to assess their depth order.

Major results: Participants were more accurate in depth assessment when illustrative shadows and supportive lines were present than when chromadepth shadows and Phong shading were used. The effects are statistically significant and the effect sizes are at least moderate. The increased accuracy corresponds to the improved confidence. At the same time, participants needed more time for the depth assessment with illustrative visualization (mean: 14 seconds compared to 11 seconds with chromadepth shadows). Thus, the interpretation of illustrative shadows and supportive lines takes time and cognitive effort. An interesting result is that the differences in accuracy depend on the locations of the points used for depth comparison. The effect was stronger when one or both points were far away (more than the average depth of the model). The experiment also confirmed the effectiveness of chromadepth shadows compared to Phong shading.

Further remarks. The results suggest that illustrative shadows and supportive lines are effective for exploring vascular trees. It is important, however, several limitations are kept in mind. First, there was no control over the display conditions. Second, the participants had a large range of expertise or background knowledge about vascular trees, vessel visualizations, and computer graphics. Third, rotation was not possible. Thus, in an interactive exploration with 3D rotation, the advantage of the additional techniques may be (strongly) reduced [LLPH15]. The effects of supportive lines and illustrative shadows were not analyzed separately.

6. Preliminary Guidelines and Research Agenda

Preliminary Guidelines. An important next step is to formulate and validate guidelines for frequent tasks in medical visualization (e. g.analysis of plaque composition, implant placement, nodule and polyp detection). So far, not enough evidence from studies is available to derive guidelines that are more than just opinions. These guidelines should state which techniques should be used and how they should be combined based on examples and counter examples. Ideally, the guidelines would be verified in perceptual experiments studying whether visualizations that adhere to them are indeed superior to reasonable baseline visualizations.

What can be said already now, is that different visualization options should be provided. No single visualization technique is optimal for both shape and depth perception. One visualization option should optimize for shape perception (e. g., with toon shading) and another one for depth perception (e. g., with pseudo-chroma depth colors). Shape perception is essential for skeletal structures and diseases that affect bones, whereas depth perception is essential to get an overview of complex anatomical structures, such as vascular trees (studies on vessel visualization focused on the depth perception). To assess a pathology at a specific point in a vascular tree, however, shape perception is important. In addition to perceptually-motivated color scales, illustrative techniques may enhance the shape perception when combined with surface shading. Complex structures are know to especially benefit from halos and depth-encoding shadows. Global illumination techniques combined with careful light source placement are key for emphasizing local shape details [ZWM13]. Local shape details may be plaques, polyps in the colon and blebs on aneurysms. The space of perceptually-motivated visualization techniques is large enough that these guidelines will not fully constrain developers—there will still be several possible techniques even for frequent and well-studied medical visualization tasks.

Design of new and redesign of existing studies. Compared to the urgent need for orientation there are only few perception-based studies. Even these studies are limited, since participants and real

Table 2: *Selected perception-based evaluations of medical visualization techniques.*

Category and Paper	Stimuli	Tasks
Blood flow [BGCP11]	blood flow and vessel surface stimuli with limited rotation allowed	gauge figure placement
Volume rendering [CRD10]	illustrative volume rendering (image- and object-based edge enhancement)	gauge figure placement
Volume rendering [DRN*16]	volume rendering in desktop-based VR with volumetric illumination	depth judgment task
Surface rendering [IFP97]	layered medical surfaces textured with ridge and valley lines	select points where the distance between the outer and inner surface is closest
Vessel visualization [JQD*08]	vessels visualized with halos, toon shading, and distance color blending	pairwise preference
Vessel visualization [KOCC14]	cerebral vessels visualized with fog, edge enhancement, pseudo-chromadepth	depth judgment task
Surface rendering [KHI04]	artificial surfaces (sinosoidal patterns) with texture (PCD)	shape type and shape categorization
Vessel visualization [LLPH15]	illustrative vascular surfaces, shadow and supportive lines as well as pseudo-chromadepth shading	depth judgment task
Volume rendering [LR11]	CT images with various illumination techniques	depth and size judgment tasks
Vessel visualization [RHP*06]	illustrative vascular surfaces with halos and depth-encoding shadow	depth judgment
Vessel visualization [RSH06]	vessels with and without chromadepth shadows	depth judgment
Volume rendering [SPV11]	ultrasound images with chromadepth and classic shadow	gauge figure placement, depth judgment task
Volume rendering [ZCBM14]	CT images with global illumination	feature identification task

users often differ. Some studies only have a few participants and others with more participants are web-based experiments with no control over display and illumination. Other studies have a solid experimental design but are not thoroughly analyzed (and do not report effect sizes or significance). Thus, there is a demand for refining and extending previous studies. Moreover, in a number of important areas within medical visualization, there is simply no perception-based guidance available at all. For example, it is currently not clear what the most appropriate visualization technique is for virtual endoscopy (VE), where the user inspects air-filled or fluid-filled cavities, such as the colon. We also found no perception-based study comparing different fiber-tract visualizations.

Visual realism is certainly a benefit in treatment planning since it ensures a high similarity to intraoperative views. For diagnostic purposes, more illustrative visualizations that emphasize shape features may be more appropriate [ZBB*06]. Specific questions relate to the value of an integration of shading and other shape cues.

Combined visualization of instruments and anatomical data. Often medical image data is visualized along with instruments, such as biopsy needles, stents, electrodes, and implants of all kinds. The precise location of instruments relative to anatomical structures needs to be conveyed. We know of no perception-based studies that compare different visualization techniques for such problems.

Perception-guided visualization of blood flow. Compared to the large variety of blood flow visualizations [VPvP*14], only few techniques are perceptually-motivated and only one was evaluated in a quantitative study. This evaluation relates to the nested visualization problem of displaying vascular structures and embedded flow. There is relevant research on *flow perception* (e. g., how to convey flow direction and orientation effectively [War08]) which can be used for guidance. Designing perceptually effective blood flow visualizations is particularly challenging for unsteady flow and has to consider *motion perception* as well.

Exaggerated shading. One perceptually-motivated technique for displaying shape is exaggerated shading (ES), where subtle local changes of the geometry are performed to enhance features [RBD06, ZCF*10]. The deliberate emphasis of surface features may be beneficial for educational applications.

Multimodal medical visualization based on combined scanners, such as PET/CT and PET/MRI scanners, is increasingly important. The visualization challenge is to fuse these images in a visualization such that the essential information from both datasets is visible and the overall visualization conveys the shape and depth information correctly. Many multimodal visualization techniques have been developed, but there is no empirical, quantitative comparison between them.

The role of reflection. Certain established depth and shape cues have not been considered in medical visualization so far. For instance, specular reflections, as they may also occur at some body organs, reveal a lot of information on spatial relations [FTA04]. The effect of specular reflection is worth investigating (e. g., for virtual colonoscopy, where a procedure is simulated that includes real-life wetness and reflections).

Patient-doctor communication. Medical visualizations—in particular perceptually-motivated, illustrative visualizations—have a great potential for patient-doctor communication and for interdisciplinary discussions (e. g., in a tumor board). In both settings, users include those that are not familiar with slice-based visualizations and benefit from visualizations that emphasize important features and abstract from unnecessary details. Only very few papers mention these use cases and even fewer assess whether medical visualization techniques are indeed useful for such use cases.

Perceptual consequences of interaction. In this survey article, we discussed the influence of enhanced visualization techniques on shape and depth perception. Ultimately, an enhanced understanding of the spatial relations is desired. Advanced interaction techniques, such as cutting, (selective) clipping, lens-based exploration, and virtual resection contribute to this spatial understanding of 3D medical visualizations. It remains to be investigated how variants of these interaction techniques and combinations with the visualization techniques influence spatial understanding.

More clinically relevant studies. The most important goal of medical visualization is to support diagnostic and treatment decisions in clinical practice, where 3D visualization techniques are incorporated in complex software assistants. To understand the consequences of decisions relating to visualization techniques, experiments with clinically-used software assistants (or very similar research prototypes) are required. Clinical decision situations, such as tumor board meetings, should be simulated to investigate, for example, whether the assessment of tumor infiltration changes as a consequence of advanced light source placement or global illumination. More studies are needed that focus on specific clinical tasks with medical experts as test persons. Such studies can reveal the influence of improved perception on cognitive processes, such as the selection of a treatment option. The ultimate goal is to understand whether the use of advanced visualization techniques matters for clinical decisions.

Explore relations to other areas. Medical visualization has some special requirements based on the peculiarities of medical image data and the complex anatomical shapes to be depicted often along with instruments or simulation results. There are, however, similarities to other areas, such as in the visualization of plants and animals that also exhibit organic shapes as well as molecular visualization. Thus, an analysis of visualization techniques developed in these areas may inspire future medical visualization development.

7. Concluding Remarks

The potential of 3D medical visualizations can only be exploited if findings from visual perception inform the selection of visualization techniques and parameters. There are already a number of studies on the influence of visualization techniques on aspects of visual perception that were carefully prepared, conducted, statistically analyzed and interpreted, serving as a valuable source of information. Given the large variety of clinically relevant tasks, however, more studies are required. Most of the existing studies were inspired by clinically-relevant tasks, but were abstracted to provide more general hints and also to enable non-specialists as participants. The perception of local shapes and the assessment of spatial relations are particularly relevant (recall [ZCBM14]). Substantial evidence exists that global illumination and the use of multiple light sources significantly improve the perception of anatomical shapes. Such advanced visualization techniques are currently not widely available in medical imaging and visualization tools. With the growing performance and improved programming options of recent GPUs these rendering techniques may become feasible such that even large medical datasets can be explored.

Perceptually motivated medical visualization also involves techniques that deliberately deviate from realistic rendering. Since gray scale images are displayed in medical image data, color may be used to emphasize either shape (*toon shading*) or depth relations (*chromadepth, distance color blending*). Boundary emphasis techniques support object recognition in dense anatomical regions. Feature lines and hatching textures may be overlaid to shaded surfaces to improve the shape perception [CRD10, IFP95]. Feature lines in isolation, however, are too sparse to faithfully depict anatomical shapes.

Halos and depth-encoding shadows support the visualization of fiber tracts and vascular trees. Line drawings that emphasize salient features of complex surfaces or hatching that encodes the depth or distances between objects were also shown to improve visual perception of these structures. A significant improvement of shape and depth perception with these visualization techniques has been demonstrated for complex medical visualizations involving elongated and branching structures, such as vasculature and DTI fiber tracts. For a given medical visualization task, no single perception-based visualization is superior to all others. A small set of visualizations that emphasize shape and depth, providing local and global illumination is most likely the best solution for a wide range of tasks. The views need to be synchronized to enable efficient exploration. In addition to these low-level illustrative techniques, also high-level illustrative techniques, such as cutaways and ghostviews that adapt the visibility of key objects have shown to be beneficial.

Acknowledgements. We thank the authors that let us use their images for our survey. For fruitful discussions on this manuscript we thank Christian Hansen, Maria Luz, Felix Ritter, and Ivan Viola.

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