Void Space Surfaces to Convey Depth in Vessel Visualizations

Julian Kreiser, *Student Member, IEEE,* Pedro Hermosilla, *Member, IEEE,* and Timo Ropinski, *Member, IEEE*

Abstract—To enhance depth perception and thus data comprehension, additional depth cues are often used in 3D visualizations of complex vascular structures. There is a variety of different approaches described in the literature, ranging from chromadepth color coding over depth of field to glyph-based encodings. Unfortunately, the majority of existing approaches suffers from the same problem: As these cues are directly applied to the geometry's surface, the display of additional information on the vessel wall, such as other modalities or derived attributes, is impaired. To overcome this limitation we propose *Void Space Surfaces* which utilizes empty space in between vessel branches to communicate depth and their relative positioning. This allows us to enhance the depth perception of vascular structures without interfering with the spatial data and potentially superimposed parameter information. With this paper, we introduce *Void Space Surfaces*, describe their technical realization, and show their application to various vessel trees. Moreover, we report the outcome of two user studies which we have conducted in order to evaluate the perceptual impact of *Void Space Surfaces* compared to existing vessel visualization techniques and discuss expert feedback.

Index Terms—Depth Perception, Void Space Surface, Chromadepth.

1 Introduction

Visualization is of key importance in many areas of medicine, such as surgery planning or education. There has been focus on improving the perceptual capabilities of these visualizations [29]. Realistic lighting simulations [24], illustrative techniques [7], or different color schemes [3] are just some of the approaches that have been proposed in order to improve shape and depth perception.

Vascular structures are composed of numerous branches, which are complex by nature and can easily clutter the resulting visualization. This makes it difficult to infer the relative position of the individual branches even when realistic lighting effects are used. To further complicate matters, additional information associated with the surface of a vessel needs to be communicated. Such information can be derived parameters like blood flow, pressure, or wall shear stress, which are typically conveyed by stream lines, different color scales, or glyphs. Effectively communicating all this information without overwhelming the viewer is a problem that has been addressed by several authors in the past [2], [19], [22], [32].

First, stereoscopic rendering is one of the most effective methods to communicate depth and shape of 3D objects. However, it usually requires the instrumentation of the user and is thus not widely available for most of the domain experts. Second, another commonly used technique to improve depth perception is chromadepth (CD) color coding [1], [35]. While its perceptual benefits can be exploited when viewing appropriately coded images without special glasses, the effect can be further supported by using diffraction grating glasses. This was also exploited by the pseudo-chromadepth (PCD) technique, which uses a color scale composed of only two colors (blue and red) to effectively convey depth [32]. The authors could show that the reduced number of colors significantly improves the depth perception as compared to chromadepth. While these approaches work well when communicating vessel structures, they do not allow the communication of additional information since they exploit the color channel to encode depth.

Thus, various approaches have been considered to overcome this problem. Behrendt et al. [2] introduced a technique to encode information on the vessels whilst maintaining the benefits of the pseudo-chromadepth color scale by applying it on the edges of the vessels only in a similar way as the Fresnel equations compute the reflection term. Lichtenberg et al. [22] used glyphs to communicate depth on the vessel end-points, freeing the surface of the vessel. Despite these efforts to integrate the visualization of several vessel parameters into a single image, it is still challenging to encode additional information. The applied depth perception techniques are either exploiting the color channel, which is simultaneously used to communicate the vessel structure, or force the user to interpret glyphs in order to decipher depth relations. To our knowledge, no monoscopic vessel visualization technique exists, which naturally encodes depth without blocking the vessel's surface.

Contribution. In this paper, we present *Void Space Surfaces* (VSS), a novel approach to visualize vascular structures. VSS is able to convey the depth of complex vessel structures without interfering with additional measures visually encoded on the vessels' surfaces. To do so, VSS takes advantage of the empty space between vessels to generate camera dependent height fields, which serve as a canvas to convey depth (see Figure 1). We will show how to generate VSS and how it can be used to convey the depth of vascular structures by applying the most commonly used depth cues: Chromadepth, pseudo-chromadetph, occlusions, or dark-means-deep. To demonstrate the capabilities of VSS, we further have conducted two user studies in which we compared VSS with previous vessel visualization techniques.

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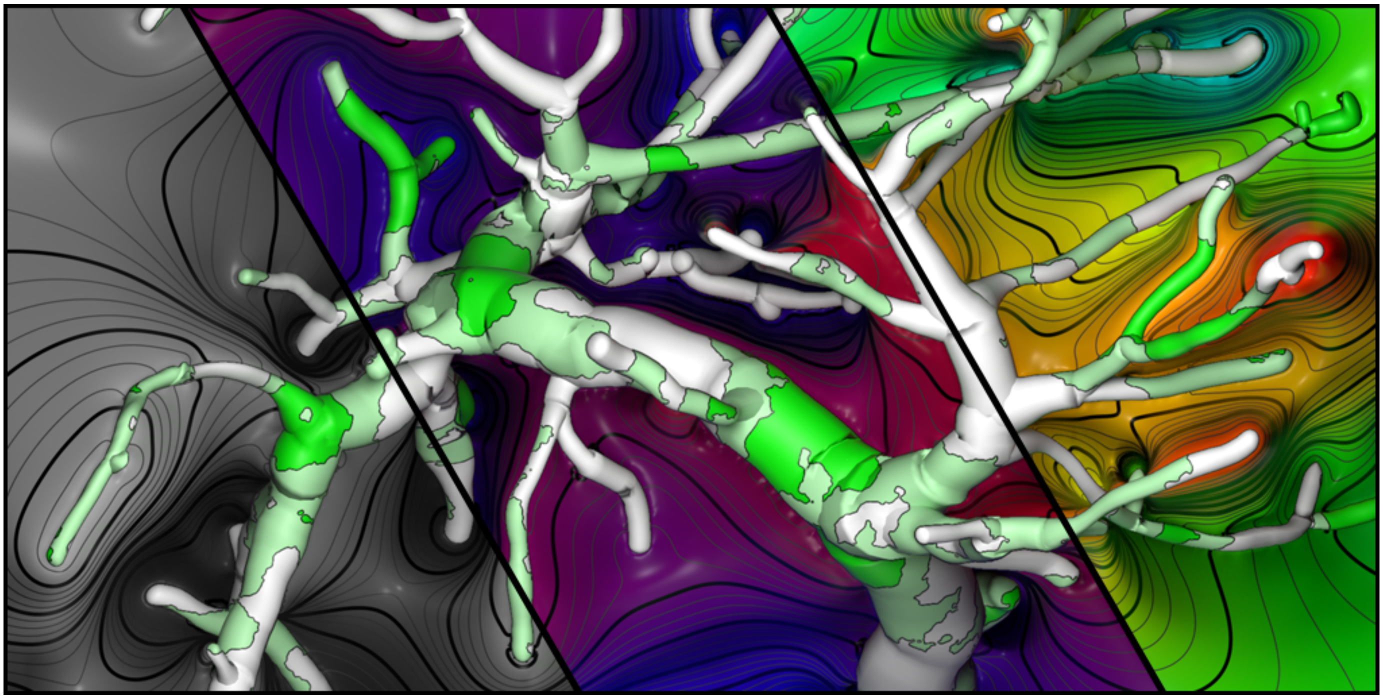


Fig. 1: Example of a vascular structure visualized using our technique, Void Space Surfaces. Our technique takes advantage of the empty space between vessels and interpolates a surface between them in which different depth cues can be applied, such as dark-means-deep (left), pseudo-chromadepth (middle), chromadepth (right), or advanced illumination techniques and iso-lines (all figures). Moreover, since depth cues have been shifted away from the vessels' surface, additional information can be encoded on them.

2 Related Work

In this section, we describe the work related to vessel visualization and depth perception enhancement in the medical field. Since providing a full review of these topics is beyond the scope of this paper, we would like to refer the reader to the state of the art report by Preim et al. [29] which details many of these concepts.

Medical visualization. Several techniques have been proposed to improve the perception of medical visualizations. Global illumination techniques, for example, have been proven to improve the perception of surface features in volume visualization [40]. Ropinski et al. [31] and Diaz et al. [11] developed different techniques to approximate ambient occlusion in volumetric datasets to improve shape and depth perception. In a more general setup, Wanger et al. [39] demonstrated how shadows can significantly improve the perception of the relative position of objects in a scene. Šoltészová et al. [37] developed an illumination model based on the work of Schott et al. [33] which was able to generate realistic shadows in volumetric renderings. Besides simulating realistic lighting effects, illustrative techniques have also been used to improve perception in medical visualization. Bruckner et al. [7] proposed *Style Transfer Functions*, which realizes non-photorealistic rendering in the context of volume visualization. Šoltészová et al. [38] applied chromadepth to improve shadow perception in volume visualization, and Ebert et al. [12] applied different illustrative techniques such as halos, boundary enhancement, and silhouettes in volume visualization.

Maximum Intensity Projection (MIP) is used to visualize contrast-enhanced medical data. This technique, due to the lack of shading, makes it difficult to perceive the relative depth of individual objects. Therefore, Diaz et al. [10] presented a technique to improve depth perception on MIP images. They computed a depth value while traversing the volume dataset and used this value to modify the final color of the MIP image. Bruckner et al. [8] added shading into MIP, improving depth perception and allowing a smooth transition between MIP and direct volume rendering.

Vessel visualization. Vessel datasets are often represented as a volume and then visualized by means of direct volume rendering [18]. Therefore, vessel visualization can take advantage of existing volume visualization techniques to improve shape and depth perception. However, representing such data as a volume is not the only approach used by domain experts, as volume datasets often include other tissues that have to be filtered before visualizing the vascular structures. Thus, several algorithms exist for extracting the vasculature from volume datasets and render them by using different primitives (such as meshes or truncated cones) [14], [15], [25]. Ritter et al. [30] developed an illustrative technique which uses hatch lines [28] on top of the vessels to encode occlusions between the different branches of the structure. Moreover, they also applied a stroke texture with a varying width depending on the distance to the viewer. Lawonn et al. [21] presented a technique which generated illustrative shadows with support lines and silhouettes to improve perception on vascular structures. Moreover, they also proposed a 2D visualization in which distance was encoded by different hatching styles. Another approach from Lawonn et al. [20] proposed supporting anchors together with additional illustrative hatching for improved spatial perception. Lichtenberg et al. [22] presented a different approach to communicate depth in vessel visualizations. They drew view-dependent circle glyphs on vessel end-points which encoded depth information. Moreover, they also proposed an algorithm to detect these points in vascular structures.

Whilst all these methods are focused on rendering extra information on top of the vessels, other techniques have centered their attention on communicating depth information through coloring the vessels. Ropinski et al. [32] used a color scale based on the chromadepth technique composed of only two colors which encodes depth information. This color scale, named pseudo-chromadepth, performed better than other techniques in the user study carried out by the authors, as it resulted in more accurate and faster responses. Joshi et al. [16] presented a set of techniques to improve perception in visualizations of vascular structures represented by a volume data set. The authors used a similar color encoding as the one used in pseudo-chromadepth together with other illustrative visualization techniques such as tone shading or halos. Chu et al. [9] presented a technique which combined a similar color encoding to the one used in the chromadepth technique with hatching rendering and silhouettes. Kersten-Oertel et al. [17], in 2014, carried out a user study in which they compared the effect of different depth cues on vessel visualizations. Based on the results of their study, they concluded that pseudo-chromadepth and the use of fog achieve the best improvement in depth perception.

Encoding depth information as colors on the vessel surfaces has been proven to be effective in communicating depth. However, these techniques limit the information presented on the vessels to depth information. Domain experts are often interested in visualizing also other properties on top of the vessels. This problem was addressed by Behrendt et al. [2] who combined pseudo-chromadepth with additional information on the geometry. They used the pseudo-chromadepth color scheme to shade areas close to the contour by applying a blending mask inspired by Fresnel equations. To represent the additional information they used a discretized color scale which reduced ambiguity between the surface color and the pseudo-chromadepth scale. Lawonn et al. [19] combined different techniques to convey depth together with vessel flow visualization, accurately resolving occlusions between vessels. Borkin et al. [3] used the surface of the vessel together with a 2D representation of them to communicate endothelial shear stress.

3 Design Goals for Vessel Visualization

The visualization techniques proposed in this paper have been developed with certain design goals in mind. While these goals are targeted for vessel visualization, we believe that many of them are also relevant for medical visualization in general and beyond.

Morphological features. When inspecting complex 3D structures such as vessel trees, it is of uttermost importance that depth and shape are communicated effectively. Besides the global shape, also the details on the surface of a vessel need to be communicated, as these might give hints to initial aneurysms or other abnormalities.

Functional parameters. Such parameters include wall shear stress and pressure in hemodynamics, elasticity, occurrence of plaque, or vascular constrictions. As in many subareas of medical visualization, in which multiparametric or multimodal data needs to be visualized, it is essential to visualize these functional parameters in the context of the morphology, because only then the association between function and structure becomes possible. Consequently, most existing visualization techniques convey the functional parameters as being overlaid over the vessel. While this interferes with the communication of surface details through shading, research related to color constancy suggests, that this approach still maintains a reasonable perception of the individual objects [13]. Nevertheless, the mapping of functional parameters exploits the same color channel as already used to communicate the vessel's surface structure. Therefore, it can not efficiently be exploited to communicate additional depth cues.

Instrumentation avoidance. Vessel visualization should ideally not rely on an instrumentation of the viewer, i.e., they should be effective without the need for wearing 3D glasses or using other aids. Bornik et al. [5] developed an augmented reality based virtual liver surgery planning system. While stereoscopic rendering techniques could be considered as being very effective in communicating depth, they require an instrumentation of the user via stereo glasses and are thus less desirable for medical visualizations. Furthermore, along a similar line, ideally a vessel visualization technique also works on static images. This is important, since often images are parts of medical reports, which are still today often printed and exchanged on paper.

Intuitive communication. Finally, it is essential that vessel visualizations can be intuitively interpreted. While it is certainly possible to craft dedicated visualizations which precisely communicate the depth of certain structures, it is not clear that such techniques are intuitively interpretable. Furthermore, it can be expected that such techniques add to the visual clutter and might thus even result in cognitive overload. Therefore, we assume that vessel visualizations should be natural in a way that they exploit coherent depth cues which do not require additional explanations to be interpreted.

4 Void Space Surfaces

Following our guidelines discussed above, and motivated by the usually large amounts of empty space between vessel structures, we utilize this area for the enhancement of depth and shape perception. We propose VSS, which allows us to completely eliminate all additional depth cues from the vessels' surface and shift them to usually unused regions. Thus, VSS has been designed to improve the communication of morphological structures, while at the same time allowing for mapping functional parameters onto the vascular surface without interference.

We do not distinguish between mesh or volume representations for vessel visualizations. Our only requirement to apply VSS is the availability of a depth map which exhibits enough void space to be effectively utilized. Our visualization technique is tailored towards both, static 2D images and 3D interactive applications.

The following part describes how we generate VSS and the techniques used to support depth and shape perception.

4.1 Surface Generation

Void space surfaces are essentially a view dependent height fields synthesized between vascular structures. To generate such fields, we interpolate the depth values of each pixel along the object's contour which serves as a basis for subsequent visualization techniques.

The way the interpolated depth values are inferred for VSS is in principle arbitrary since there is no ground truth to this problem, as VSS is an artificial construct. However, the void space surfaces should be smooth to avoid the introduction of visual artifacts.

In our case we use *Inverse Distance Weighting* [34] which is smooth and has a control parameter to adjust the influence of samples depending on their distance to the target point (see Equations 1). Other spatial interpolation techniques such as *Green Coordinates* [23], *Poisson Image Editing* [27], or *Kriging Interpolation* [26] might also be usable to fill the empty areas between vascular structures. However, *Inverse Distance Weighting* has the advantages that it is easy to implement and each pixel can be calculated in parallel which makes it perfectly suitable to achieve interactive frame rates through a GPU implementation. Thus, we synthesize the depth values as follows:

$$z'(x_0) = \frac{\sum_{i=1}^{N} w(x_0,x_i) \cdot z(x_i)}{\sum_{i=1}^{N} w(x_0,x_i)}$$
$$w(x_0,x_i) = \frac{1}{d(x_0,x_i)^p} \tag{1}$$

whereby z' is the depth at an interpolated point x_0 and z denotes the sample depth at an interpolating point $x_i \in \mathbb{R}^2$ with N being the total number of points. The weight w consists of the inverse of a given distance metric d from x_0 to x_i, in our case the Euclidean distance metric. The so called power parameter p controls the steepness of the interpolation. High values of p accentuate details, low values of p produce a more smooth appearance of the void space surfaces. We found that a value of $p = 3$ is a good balance.

Depth anchoring. To enable VSS to become a canvas for communicating depth of the visualized vessel trees, it is crucial that the geometry is visually associated with the void space surfaces. Only through such an association, to which we refer as depth anchoring, the depth is intuitively transferred to the vessel structure. To implement depth anchoring in the context of our design guidelines, we have decided to exploit natural illumination effects. Figure 2 shows the effect of depth anchoring by visualizing the void space surfaces without (left) and with depth anchoring (right) achieved through global illumination. It can be clearly observed that the vessel structures seem to be aligned along the void space surfaces when enabling depth anchoring.

Unfortunately, possibly darkened cavities through global illumination could cause vessels to disappear. Shading the vascular structures independently from the void space surfaces enables the depth cue of shading while maintaining an unaffected appearance of the vessels and therefore no disadvantageous artifacts due to bad lighting through occlusion. To avoid this decoupling of shading, a light source directly positioned at the camera is also another possible solution to that issue.

To establish a clear visual connection between the void space surfaces and the vascular surface model, shading of the void space surfaces plays also a major role. If the vessel geometry and the void space surfaces are illuminated with the same lighting settings, the depth impression and scene comprehension greatly improve. Reflections on the void space surfaces accentuate cavities, hills, and neighboring occlusion which support the perception of relative and global depth differences. Either calculated with global illumination algorithms or simplified shading models, without any highlights, the void space surfaces appear rather as a flat wallpaper-like background image which requires cognitive interpretation efforts to decipher depth.

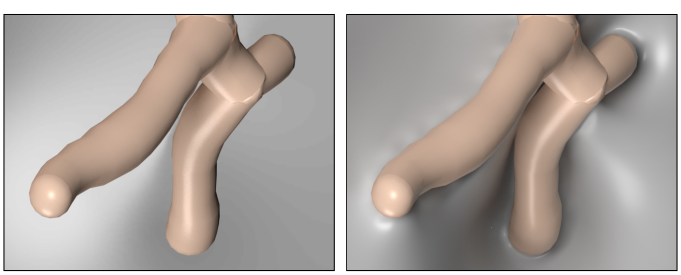


Fig. 2: These figures illustrate the same VSS without (left) and with (right) depth anchoring. The anchoring effect, which is achieved by applying global illumination, intuitively *glues* the vessel structure onto the VSS and thus enables an intuitive transfer of depth information.

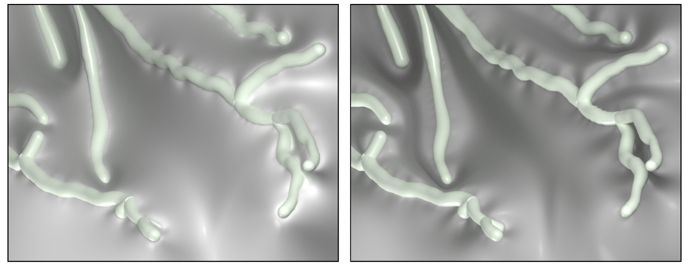


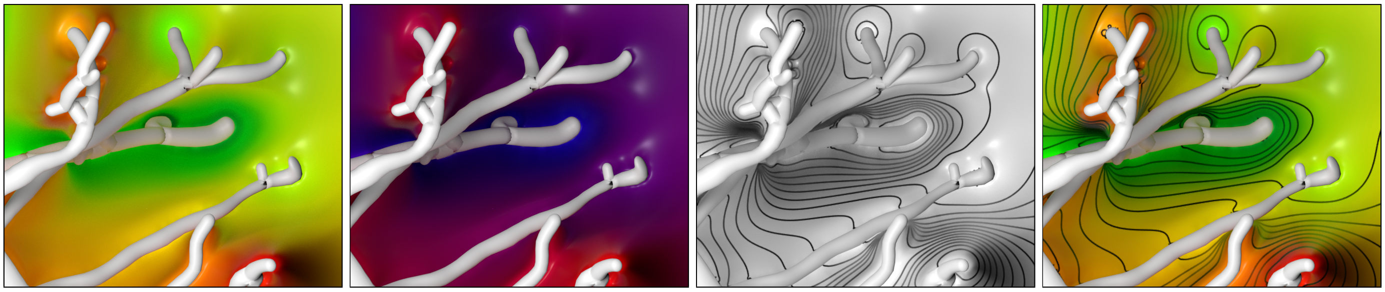
Fig. 3: The effect of parameter p on the interpolated depth values is illustrated in these figures. High values of $p = 5$ (right) increase the weight of local features while distant depth values almost do not contribute to the interpolated depth, generating sharp transitions. Lower values of $p = 2$ (left), on the contrary, create smooth transitions between the vessels.

Power parameter variation. Greater values of p result in a greater influence of samples close to the interpolated point, see Figure 3. For areas further away from the contour and without a distinct closest surface contour, the result is often a mostly averaged interpolated depth across the whole boundary. This is especially the case if a lot of contour points contribute to a pixel or the depth values along the contour are from a wide range. Local features can be preserved further into open areas with an increasing power parameter p for the interpolation which sharpens the boundaries between different levels of depth. Thus, in the most extreme case, the void space surface develop patterns similar to a Voronoi diagram.

If the vascular model does not cover a lot of screen space area, most of the surrounding pixels closer to the image border will approach the average value of the outermost silhouette. This forms a fairly dull surface which does not communicate a lot of depth and shape of the vascular model. Vessels which intersect the image border separate the VSS into multiple regions which describe their surrounding contours much more accurate. Generally speaking, for a meaningful overview and a significant global depth and shape impression, the vascular model should be kept as close as possible to the image boundary.

4.2 Perceptual Enhancement

Based on the VSS generation described in the previous subsection, we can now use it as canvas for perceptual enhancement. Thus, VSS forms a new foundation for a variety of depth enhancement techniques which have proven to be successful. Height field rendering would be the most similar field when it comes to the use of established depth and shape enhancement algorithms. In the following paragraphs, we discuss a selection of depth enhancement techniques, which we found helpful in the context of vessel visualizations. We would like to point out, that this is not an exhaustive list of possibilities, but rather a subset meaningful to illustrate the capabilities of VSS. Figure 4 shows the results of the perceptual enhancement using color-coding and iso-lines as well as their combination. In order to fully understand how the void space surfaces are attached to the vessels' geometry, Figure 5 illustrates a side view rendering of a vessel tree. Figure 6 depicts a direct comparison between the use of the perceptual enhancements without and with the depth anchoring effect. For the latter, the perceived surface is immediately more vivid.



(a) (b) (c) (d)

Fig. 4: In order to convey depth, we incorporate different depth cues on the Void Space Surfaces. We encode the depth values with two different well-known color scales, chromadepth (a) and pseudo-chromadepth (b). We also incorporate iso-lines in our visualization (c), since they provide visual cues of the shape of the surfaces. Moreover, these techniques can be combined (d).

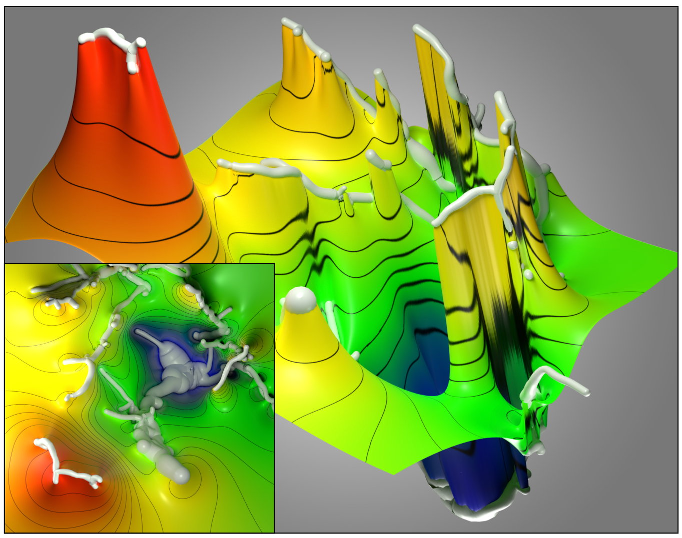


Fig. 5: Rendering of a vessel tree together with its VSS in chromadepth color scale. This side view perspective – together with the viewer's perspective – shows the smooth appearance of VSS and how they are directly attached to the vascular geometry. The thick appearing, black iso-lines are due to the large depth coverage of those areas from the viewer's perspective. We keep the line width constant in screen space so they appear thicker when viewing them from the side. This illustration shows iso-lines shifting in depth due to the mesh generation process. However, this is not visible in the final visualization because of the different viewpoint.

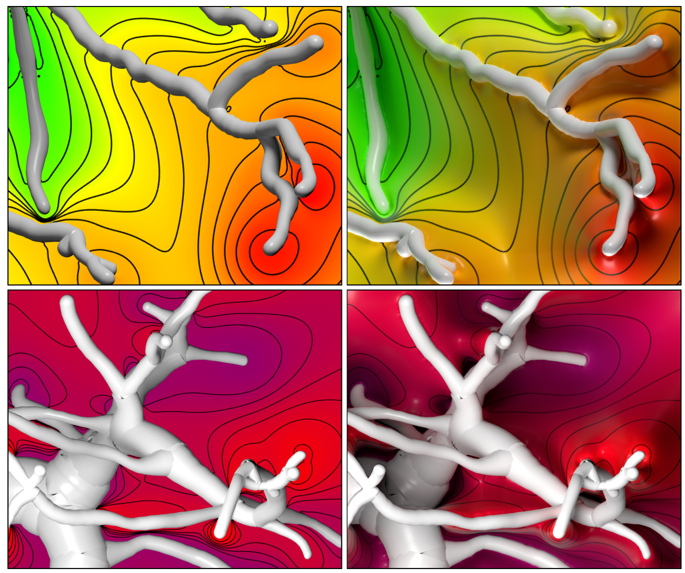


Fig. 6: Even with depth cues such as pseudo-chromadepth or iso-lines, illumination is one of the most effective ways to convey depth and shape. In these figures, we illustrate the improvement in depth perception achieved by shading the VSS using global illumination (right) over flat shaded background depth cues (left).

Color-coding depth. Color and brightness are commonly used to communicate depth in vessel visualization [3], [17], [32]. For VSS, we use the chromadepth and pseudo-chromadepth techniques, exploiting the effect that shorter wave lengths are refracted more than longer ones at the lens of the eye. This creates the illusion of depth in 2D images. The full chromadepth range contains more than two colors which have no order beside their corresponding wavelength, which can be confusing for users. Especially colors such as yellow appear brighter compared to red and can therefore wrongly be perceived closer. The reduction to pseudo-chromadepth with blue (far) and red (close) does not suffer from this issue. Alternatively, the dark-means-deep metaphor can be used if depth values are mapped to black (far) and white (close) as monochromatic color scale. This supports people with any sort of color blindness while still being expressive for everyone.

Iso-lines. Inspired by topographic maps, we also introduce iso-lines which are displayed on the void space surfaces to support shape perception. The elevation of the surface are indicated by the form and density of the level sets. More iso-lines help to convey local changes, but too many can lead to clutter at large depth differences, especially between close structures. In the case of neighboring structures which are adjacent to the same void space, iso-lines help to distinguish points with small depth differences more easily. A comparison of different numbers of iso-lines on the void space surfaces is presented in Figure 7. An additional benefit of iso-lines is also that depth differences can directly be inferred when comparing two points located on different levels. To further extend this cue, we added secondary, thinner iso-lines as a ruler metaphor. These help to depict local changes while leaving enough room for other cues, such as color, which would otherwise be overdrawn, especially in steep areas. A comparison between only primary and primary together with secondary iso-lines can be seen in Figure 8.

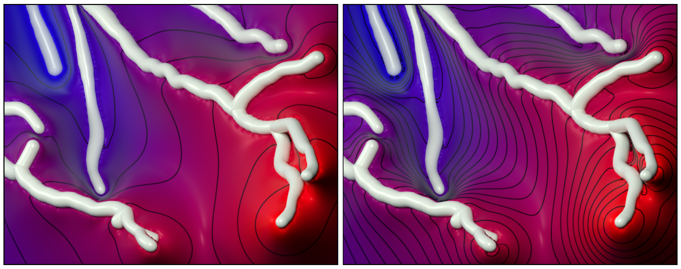


Fig. 7: Iso-lines describe the shape of a height field and help to convey depth and shape. A high density of iso-lines communicates areas with a large gradient. Here we illustrate the effect of varying the number of iso-lines (left: 8 levels, right: 32 levels).

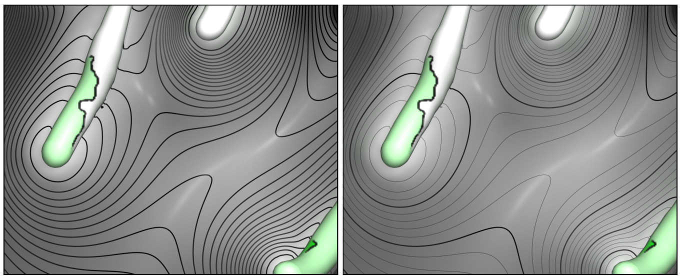


Fig. 8: Secondary, thinner iso-lines between the primary ones make the visualization less cluttered, especially in steep areas where they tend to occupy a lot of screen space, overdrawing cues like color.

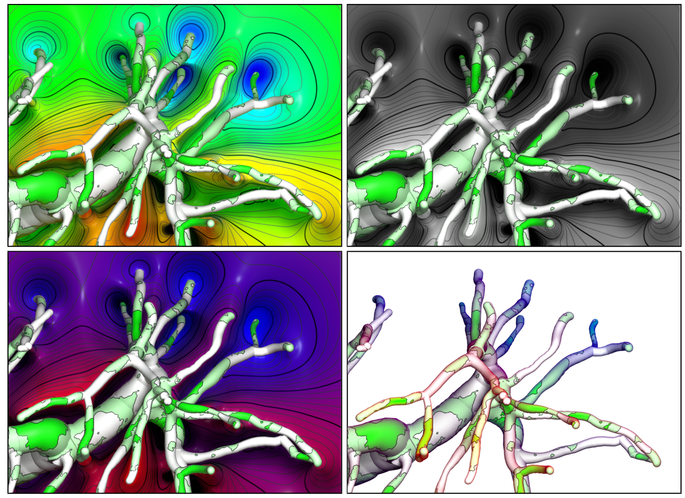


Fig. 9: Functional parameters can be mapped onto the vascular surface without direct color confusion by using VSS. This figure compares the CD, monochromatic, and PCD color scale on our VSS together with functional parameters on the vessels. The Image on the bottom right shows a comparison of the same dataset rendered with the technique proposed by Behrendt et al. [2] as a direct comparison to our version on the bottom left. With our method, depth and the relative position of the individual branches are effectively communicated, freeing the surface of the vessel to encode other relevant information. In the state of the art, the pseudo-chromadepth colors have to be desaturated in order to not collide with the additional information presented in the same area.

4.3 Functional Parameter Mapping

After all depth cues have been shifted away from the vascular surface model, functional parameters can be mapped on a vessel's surface without resulting in interference as shown in Figure 9. While communicating information such as wall shear stress or pressure, the applied color coding of these properties has to be considered. For the best contrast to the VSS, complementary or unused colors should be used instead of similar ones. The pseudo-chromadepth color map has the advantage of fewer colors compared to chromadepth, which could be ambiguous. The monochromatic color scheme can be used the completely eliminate this problem.

5 Implementation Details

Static 2D images of vascular structures are often used to analyze scans or to communicate results. However, inspecting the 3D model of these structures interactively can further increase the effectivity of the tasks carried out by domain experts. Therefore, we propose in this section an interactive GPU-based implementation of VSS.

5.1 GPU Pipeline

The first step of our GPU pipeline is the rendering of the 3D vessel model. Since VSS only requires a depth buffer as input, they are independent of the technique used to render the vessels model. Thus, both rasterization of triangular meshes or direct volume rendering can be used in this step. Once the depth buffer is generated, our algorithm linearizes the depth values.

In order to be consistent among different near and far plane configurations, we perform an additional pass to normalize the depth values. In this step, we determine the minimum and maximum depth values (without considering the background values), and use them to normalize all depth values to the range $[0,1]$. This allows us to easily map the depth to an arbitrary color map.

To generate VSS, we have to distinguish between closed empty areas, the void spaces, and the pixels of their contours. We use the algorithm proposed by Suzuki et al. [36] to compute the pixels of the different contours in the image and the hierarchy between them. Thanks to this hierarchy we are able to determine the inner and outer contours of each empty area between the vessels. In our pipeline, we use the CPU implementation of this algorithm from the OpenCV library [6].

The indices of the contour pixels of each void space and which pixels belong to them are then uploaded to the GPU memory. The last step of the pipeline renders a screen-aligned quad and computes the depth values for all pixels using Equation 1. Then the interpolated depth is used to determine the color of the pixel based on the desired color scheme, CD or PCD, before we generate the iso-lines. Additionally, our fragment shader reconstructs a 3D position and normal in viewspace with which the illumination is computed.

5.2 Performance Measurements

We evaluated the performance of our GPU implementation on a computer with the following configuration: Intel i7 at 3.6 GHz, 16 GB of RAM, a GeForce GTX980, and a screen resolution of 1280×720 pixels. We measured the milliseconds required to compute the VSS without considering the time required to render the vessel model, as this can be exchanged. The values obtained for the different configurations tested are presented in Table 1. To investigate the effect of different void space sizes, we evaluated our algorithm with three different camera configurations: one far

TABLE 1: In this table, the milliseconds required to generate and render the VSS is presented. Moreover, we provide the number of contour points for all independent empty areas in parenthesis.

	Far (15 - 10 K)			Medium (17 - 5 K)			Close (35 - 2.5 K)		
Step size	1	3	5	1	3	5	1	3	5
ms	165	114	60	105	69	47	64	40	25

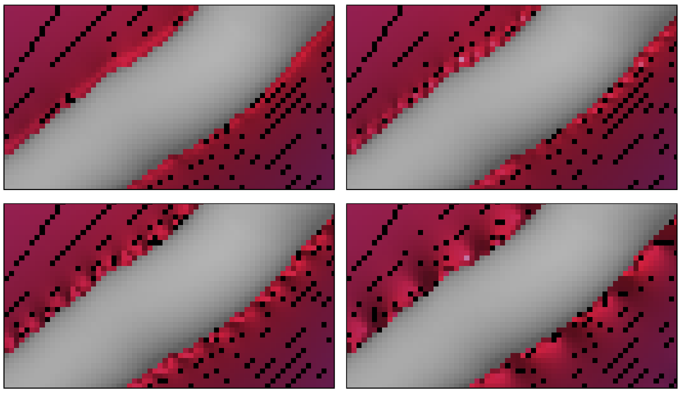


Fig. 10: Zoom-in images (~factor of 3) comparing the visual artifacts obtained when skipping contour pixels during the depth interpolation in void spaces. In these figures, from the top left to the bottom right, a step size along the contour of 1, 3, 5, and 10 is applied. Note that even for a large step size such as 5 the visual artifacts are almost not noticeable, whilst it increases performance by more than a factor of 2. Because the step size is always in pixel space, the visual artifacts are better visible when zooming in.

away from the vessels in which the branches do not intersect with the borders of the screen (column *Far* on Table 1), a camera at a medium distance in which the object intersects the screen borders only in a few places (column labeled as *Medium* on Table 1), and a close view in which the vessels intersect with the screen borders at several places (*Close* column on Table 1).

The results of these experiments show that the worst performance was obtained with the distant camera, which is due to two different facts. First, the number of pixels for which the interpolated depth value has to be computed is higher than in close-up camera configurations. Second, in these configurations, most of the pixels of the void space surfaces belong to the same big void space since the vessels do not intersect with the image borders. The contour of this area is composed of a high number of pixels that have to be iterated in order to properly interpolate the depth value in the void space surfaces, thus slowing down the performance. Table 1 also provides the maximum number of contour pixels for a single empty area and the number of contours for each visual configuration in parenthesis.

Although we achieve interactive frame rates, we have investigated further approaches to increase the achieved frame rates. Thus, instead of iterating over all the contours pixels, the fragment shader can skip a user-defined number of pixels. As presented in Table 1, the algorithm can be sped up by more than a factor of 2 by simply increasing the step size during the iteration of the contour pixels. However, this optimization is not free of drawbacks. Skipping pixels can introduce visual artifacts as illustrated in Figure 10.

6 Quantitative Depth Cue Evaluation

To evaluate the perceptual performance of VSS, we conducted two quantitative lab studies to compare against other established vessel visualization techniques. In particular, we were interested in how fast and accurate participants can judge depth. This section focuses on the comparison of the underlying depth cues. VSS is compared to the direct colorization of vessels, both without functional parameters. The following Section 7 compares our best performing setup to the current state of the art from Behrendt et al. [2]. We designed the comparative studies as within-subject.

The approaches we used were three different 3D visualization techniques – two of them in two variations. The first pair consists of a neutral vessel material and our VSS with iso-lines and global illumination, one with chromadepth (VSS-CD) and the other using pseudo-chromadepth (VSS-PCD). The second pair applies the chromadepth (vessel-CD) and pseudo chromadepth (vessel-PCD) color scale using global illumination directly onto the vascular surface as introduced by Ropinski et al. [32]. Finally, we utilize a neutral vessel rendering (baseline) using global illumination without additional depth cues as baseline. The labeling for each of the five configurations in parentheses is used in all further descriptions and figures as short notation.

6.1 Hypotheses

To evaluate participants ability to make fast and therefore intuitive judgments on a given task, we decided to measure response times as well as accuracy. Therefore, we have formulated four hypotheses about what we expect from the compared visualization setups.

1) The baseline performs worst in both aspects (response time and accuracy).
2) Due to the indirectness, the response time if using VSS is slower compared to depth cues directly rendered on the vessel's surface.
3) VSS and the direct vessel rendering perform similar in terms of accuracy.
4) Based on the findings by Ropinski et al. [32], we hypothesize that the pseudo-chromadepth color mapping of both setups, with and without the VSS, is superior to their chromadepth version in both aspects (response time and accuracy).

6.2 Stimuli and Task

To minimize complexity and cognitive load, each image presented to the participant consists only of a vascular structure and two markers pointing on the model's surface. Figure 11 shows an example of our used marker design and three different stimuli. The task was then to decide whether the left or right structure appears closer. We designed the markers to be as unobtrusive as possible while still clearly pointing to the spot of interest. As a result, the search time for both markers in the image had to be minimized before the actual participant's decision was taken. Therefore, we utilize a cross with four separated and spread out arms. This shape avoids too much occlusion of the actual target while still standing out due to its regular shape compared to the organic vessel appearance. The interior of the cross is colored white and the border black to achieve high contrast.

To balance the task complexity per displayed image, we placed the pair of markers according to three different criteria. Their distance in screen space, target depth difference, and if they are directly connected through the void space. We assured that the

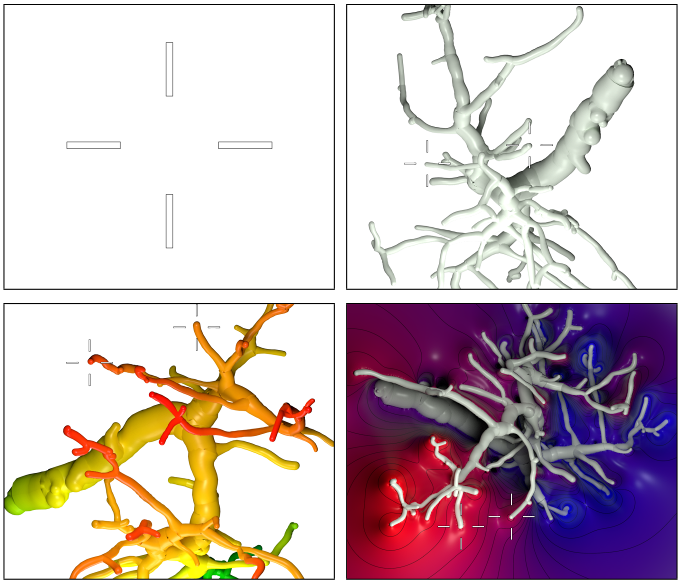
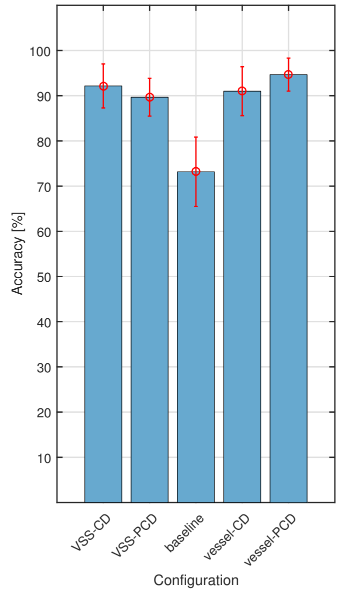
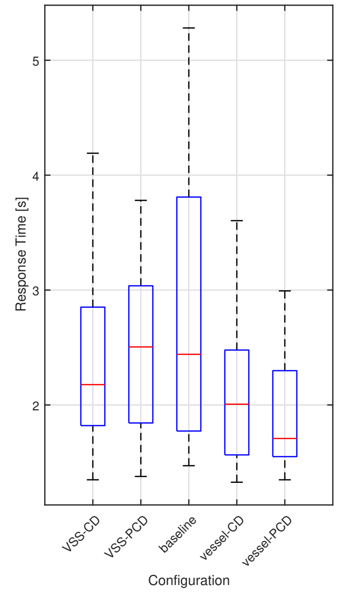


Fig. 11: In our first user study, we presented to the participants several figures generated using different configurations, such as plain shading (top right), colored vessel (bottom left), or colored VSS (bottom right). Two points of the vessel structure were highlighted by using the marker on the top left. The participants had to select the closest point to the camera between them.



(a) Error bar chart for accuracy in percent per visualization system.



(b) Box plot for response time in seconds per visualization system.

Fig. 12: For each participant in our initial study, we measured the accuracy (a) and response time (b) during a depth judgment task. The shown statistics represent 20 participants with each of them assessing 150 stimuli.

markers are at least 10% of the total depth difference in the image apart and clearly separated into left and right.

Using our visualization techniques (5), different vascular models (6), and different positions of markers (5), we create a total of 150 stimuli.

6.3 Participants

We conducted the evaluation with 20 participants from our university campus population (5 female, 15 male), aged 22 - 34 ($M = 30$, $SD = 3.1$). We excluded one participant from further analysis, because of error rates at $\approx 50\%$, indicating that the given task was not understood well enough. All participants had normal or corrected to normal vision and none of them had any further perceptual impairments such as color blindness.

6.4 Procedure

At the beginning of the study, we briefly explained the topic of depth perception. Then, for the controls of our application, we introduced a left ('F') and right ('J') key corresponding to the left and right marker respectively. Participants were instructed to give an answer as quickly as possible, while still making sure to be certain about which point appears to be closer to them.

Each stimuli was preceded by a focus screen showing a countdown for three seconds before presenting the stimuli. After a response was given, participants had the chance to focus again, before moving to the next stimuli by pressing the space bar. This neutralizes the previously displayed stimulus and assures that the participant is prepared to give an answer.

Participants started the survey by completing a training phase to familiarize with the task. The participants were not limited in the time to feel familiar with the process. Then, the main evaluation was presented consisting of our stimuli as described in Section 6.2. The set of images with all configurations was randomized and counterbalanced using Latin square.

6.5 Statistical Analysis

Because our study was designed as within-subject and our data is non-parametric (verified by the Shapiro-Wilk test for normality), we used the Friedman's ANOVA (analysis of variance). We found significant differences between the compared systems for the response time ($\chi^2(4) = 49.02$, $p < .001$), as well as for accuracy ($\chi^2(4) = 43.68$, $p < .001$). An additional post hoc analysis with Bonferroni correction exhibits all pairs of visualization configurations where a significant difference exists.

All of the depth enhanced visualizations performed similar and outperformed the neutral baseline rendering in terms of accuracy. In all cases the critical difference was 28.1 with observed differences of VSS-CD $= 50.5$, VSS-PCD $= 39.5$, vessel-CD $= 46.0$, and vessel-PCD $= 64.0$. Error bar charts for each of the techniques are shown in Figure 12a.

As to response times, we found significant differences between the methods which use depth cues directly on the vascular surface (vessel-CD and vessel-PCD) and all three other configurations (VSS-CD, VSS-PCD, and the baseline). The critical difference is the same as for the accuracy measurements with 28.1. The pairwise observed differences are VSS-CD $\leftrightarrow$ vessel-CD = 34.0, VSS-CD $\leftrightarrow$ vessel-PCD = 48.0, VSS-PCD $\leftrightarrow$ vessel-CD = 34.0, VSS-PCD $\leftrightarrow$ vessel-PCD = 48.0, baseline $\leftrightarrow$ vessel-CD = 36.0, and baseline $\leftrightarrow$ vessel-PCD = 50.0. Box plots presenting all timing measurements are shown in Figure 12b.

7 State of the Art Comparison

Our user study in Section 6 takes into account the enhancement of depth perception from Ropinski et al. [32] using the CD and PCD color scheme directly on the vessel tree as shown in Figure 13.

In this section, we compare our technique with the method proposed by Behrendt et al. [2] – both with the PCD color

Fig. 13: Comparison between our method (top figures) and the chromdepth (bottom left) and pseudo-chromadepth [32] (bottom right) methods.

scheme – and a neutral baseline through another user study. In this experiment, all three visualization styles have additional parameters on the vessels' surface to represent the intended use case. Figure 9 presents a comparison of the same model.

We describe only the differences to our first study, by reason that the setup, task, and procedure are the same.

7.1 Hypotheses

We framed different hypotheses for our evaluation with functional parameters on the vessels' surface. The intent to measure response time and accuracy is the same as in our first study.

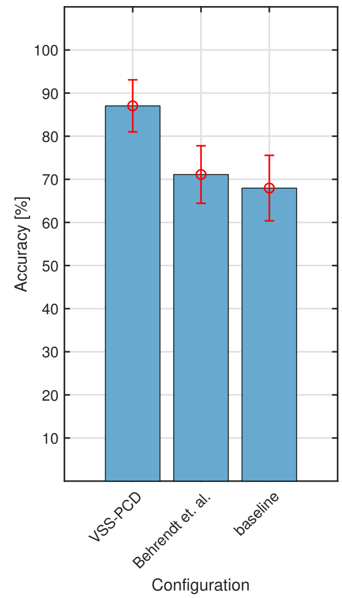
1) VSS-PCD performs better in terms of accuracy than Behrendt et al. and the baseline, due to the full visibility of the void space surfaces and no overlap in information channels (depth cue and functional parameter).
2) Behrendt et al. performs better in terms of accuracy than the baseline as shown in their work.
3) Based on the finding of our first study, all three techniques have a similar response time.

7.2 Stimuli

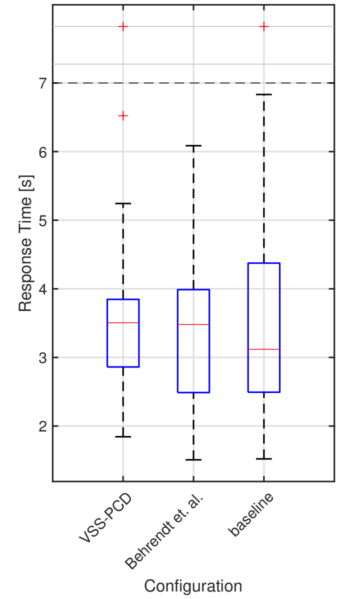
Using our visualization techniques with added functional parameters (3), different vascular models (6), and different positions of markers (5), we created a total of 90 stimuli.

7.3 Participants

In our first study, all subjects were part of the general public. For the subsequent state of the art evaluation, 18 experts from medicine (15) and biology (3) participated (10 female, 8 male), aged 19 - 34 ($M = 23.7$, $SD = 3.6$), of which 4 were PhD students and 14 regular students in the semester between 3 and 10 ($M = 5.9$, $SD = 2.7$). All participants, except one, had normal or corrected to normal vision and none of them had any further perceptual impairments such as color blindness.



(a) Error bar chart for accuracy in percent per visualization system.



(b) Box plot for response time in seconds per visualization system.

Fig. 14: For each participant in our state of the art comparison study, we measured the accuracy (a) and response time (b) during a depth judgment task. The here shown statistics represent 18 participants with each of them assessing 90 stimuli.

7.4 Statistical Analysis

Due to the same study design as already discussed in Section 6, the same analysis of the data is performed.

We found significant differences between the compared systems only for accuracy ($\chi^2(2) = 25.86$, $p < .001$). The response time was similar for all three techniques ($\chi^2(2) = 2.11$, $p = .35$).

In terms of accuracy, VSS outperformed both, the method from Behrendt et al. and the baseline. In both cases the critical difference was 14.36 with observed differences of VSS-PCD $\leftrightarrow$ Behrendt et al. $= 23.0$ and VSS-PCD $\leftrightarrow$ baseline $= 28.0$. We could not find a significant difference between Behrendt et al. and the baseline. Error bar charts and box plots presenting all timing measurements for each of the techniques are shown in Figure 14.

8 Expert Feedback

In addition to our quantitative evaluation in Section 6 and Section 7, we consulted an independent senior doctor to receive further feedback about our new visualization design. He finished his studies in 2008 and habilitated in 2018, specializes in internal medicine and gastroenterology, and leads a gastroenterological laboratory and an internistic emergency room. The goal of the interview was to identify useful aspects and potential drawbacks. This qualitative evaluation was twofold. First, discussed the general aspects of our visualization. Second, a comparison of VSS with the state of the art from Behrendt et al. [2] was performed to inspect differences between both techniques.

Study Setup. In the beginning, we introduced the expert to our visualization and demonstrated via example cases how depth is conveyed using VSS with its different cues like shading, color, or iso-lines. The presented examples were of both forms, static images and our interactive implementation which the expert could explore and change all parameters to analyze the potential of VSS. After the general idea of VSS had become clear to the medical expert, we discussed the following major topics: different parameter settings, the look-and-feel, possible improvements, and a comparison to the state of the art from Behrendt et al. [2].

General feedback. The first comments were regarding the different color schemes. The full CD color scale was immediately perceived as too distracting for the expert. The reason was too much color variation in the whole image together with the functional parameter mapping. There was no preference between the PCD and monochromatic colorization, both felt convenient to work with. For the black and white gradient, one remark was that distant areas of the void space surfaces should not become too dark.

The feature which supported the shape perception the most from the expert's point of view was the different types of iso-lines on the void space surfaces. A combination of primary and secondary iso-lines seemed very helpful in the process of understanding the structure of the vessel tree. The expert favored a larger ratio of secondary to primary iso-lines, especially compared to the exclusive use of primary ones.

The next discussion point was the power parameter p of the interpolation. If the exponent was set too high, forming plateaus would cause iso-lines to vanish, which were the most valuable cue to the expert. On the other hand, if the exponent was set too low, VSS becomes not particularly helpful due to the uniform and smoothed out appearance. A value between 3 and 4 worked best for the expert for all tested models as then the void space surfaces do not develop distinct plateaus. Simultaneously, all iso-lines remain clearly visible and the color coding is distinct enough as depth cue.

There were also three general comments about VSS. Occasional artifacts around the vessel border at fine details draw attention, smoothing them out might be an important addition to reduce the distraction to a minimum. Regarding the perception of depth using VSS, a comment was that indented structures are perceived more prominent compared to protruded ones. This may be due to the fact that vessels in forming cavities have more geometry around them to interact with compared to more isolated, sticking out geometries. Lastly, a positive comment was that the view dependent void space surfaces in our interactive implementation were not perceived to be disturbing or distracting at all.

Overall, the medical expert concluded that VSS can be a valuable addition to currently used visualizations in clinical routine.

State of the art comparison. After the general interview, we asked the medical expert for a comparison between VSS and the state of the art visualization technique from Behrendt et al. [2]. There were two main aspects for which we received comments.

First, VSS was perceived equally helpful by the expert when it comes to the recognition of the overall vessel structure. However, one possible shortcoming of the method presented by Behrendt et al. [2] was recognized. At flat angles, where the Fresnel term gets large, the vessels' surface has the tendency of getting fully colored by the PCD color scale. This is mostly the case for vessels which closely follow the camera's view direction from front to back.

Second, a clear benefit was mentioned when it comes to the judgment of functional parameter values while still being able to clearly recognize the shape of the vessel tree. The expert's comment was that the pseudo-chromadepth or monochromatic colorization of the VSS did not interfere with the functional parameter mapping on the vessels. The combination of the full chromadepth color map as depth cue and additional functional attributes was considered not optimal, but still better compared to a plain rendering.

9 Discussion

Here, we first present the results of the depth cue evaluation from Section 6. Then, the findings from the state of the art comparison in Section 7 are discussed, before we outline limitations and possible application of VSS.

9.1 Depth Cue Comparison

The results obtained in our first user study support most of our hypotheses. Our first hypothesis states that the baseline method performs worst in response time and accuracy when providing depth cues on the vessels' surface or on the void space surfaces. The results of the user study support that both advanced techniques performed better than the baseline model in terms of accuracy. Regarding the response time, however, that was only true for the case in which depth cues were applied directly on the vessels' surface. We suppose that this is due to the indirection introduced by our method since the user needs to also focus its attention on the surrounding areas of the vessels.

Our results also support hypothesis 2. As in the previous case, the response time obtained with our method was significantly lower than the one achieved by applying depth cues directly on the vessels' surface. As mentioned before, in order to perceive the depth cues with our method, the user needs to focus their attention on the surrounding areas of the vessel, thus increasing the time until a user can judge depth.

Our third hypothesis predicted that both techniques, depth cues on the vessels and depth cues on the VSS, would achieve similar accuracy which our results also supports. Although, our method did not improve the existing technique in terms of accuracy, it achieved a similar performance whilst leaving room on the vessels' surface to communicate additional information. Contrary to the study by Ropinski et al. [32], our study could not provide support on the evidence that the pseudo-chromadepth color mapping is superior over the full range chromadepth technique.

Moreover, the participants of our user study presented a similar type of response to our images. Between VSS and vessel surface coloring, the latter appeared as the most effective in terms of speed, indicating that participants where able to make an intuitive judgment. However, for VSS, iso-lines were perceived as very helpful in the configurations in which the depth difference between the queried points was small and the points are adjacent to the same void space. Nonetheless, if the points do not share a void space, color coding was the most effective depth cue, which underlines the need for combination of depth cues. Although the color range of the pseudo-chromadepth color mapping is greatly reduced, it was perceived as most helpful. We suppose that the high performance obtained with the pseudo-chromadepth method is due to the fact that a linear relationship can be established between depth and color. The user can associate blue with far objects and red with close ones, something not possible with the full chromadepth color scale. Furthermore, some participants mentioned that the chromadepth technique was confusing since they associated yellow with close objects due to its brighter appearance. Another issue with the chromadepth color scale is its rainbow-like appearance due to several shortcomings [4]. Especially the introduction of artificial contrasts and features is problematic. Lastly, the participants of our study sorted the techniques from more useful to less useful as follows: pseudo-chromadepth on the vessels' surface, pseudo-chromadepth on the VSS, chromadepth on the vessels' surface, chromadepth on the VSS, and regular 3D rendering.

In the future, we plan to conduct further studies to investigate which depth cue has the biggest effect on the depth perception. We plan to find this out by determining which is the minimum depth a user is able to differentiate while using different techniques, and which combination of parameters performs best.

9.2 Remarks on the State of the Art Comparison

We can confirm our first hypothesis which states that VSS outperforms the method from Behrendt et al. [2] and the baseline. Although both, depth and additional parameters, are encoded by VSS and their technique in a single image, their method has to make some compromises since it uses the limited space of a vessel to encode both. The pseudo-chromadepth colors are not fully saturated to not drive away the attention of the user from the additional parameter. Our method, on the other hand, does not have this drawback. Furthermore, we are able to convey depth through larger areas in the empty space between the vessels, which does not interfere with the encoding of additional parameters on its surface and does not require reduced color saturation. While these areas were previously unused, they do not compromise the actual visualization. As commented by several study participants, the additional iso-lines on the void space surfaces help to distinguish two points with a small depth difference.

Unexpectedly, we could not confirm Hypothesis 2. The method from Behrendt et al. did not outperform the baseline. We believe this originates from thinner parts of vessel structures we have also used in our test, compared to the geometry in their study. The pseudo-chromadepth colorization of the vessels' edges is in such a case not prominent enough. It is hard to distinguish different shades of red or blue if their screen coverage is reduced, the thinner a structure becomes. This was confirmed by most participants. They mentioned that they could often just distinguish between red and blue, barely different similar colors on the gradient.

Our last hypothesis was also confirmed. The response time is similar for all three techniques as already indicated by our first study. This might be due to the fact that all methods have some sort of additional cognitive load when judging depth. VSS conveys depth indirectly, the technique from Behrendt et al. has overlapping colors and therefore a reduced visibility of the depth cue, and the baseline is inherently harder to interpret on a 2D canvas.

9.3 Limitations

Our conducted evaluations in Section 6 and Section 7 indicate that the perceptual power of VSS is on par with the full vessel colorization and superior to the state of the art, while it does not interfere with the color information of the vessels. Nevertheless, during the design of VSS we have also identified limitations which we would like to discuss in this section.

Necessary void space. The first and most obvious drawback is the necessity of void space between geometries of interest. Vascular structures satisfy this requirement quite well, due to high enough scanner resolution available nowadays, and are therefore our main application scenario.

Background structures. The second scenario in which our method does not work is the case if an object shares no contour with the background and is therefore not attached to the VSS. This happens if a structure lies completely in front of another one and gets occluded from the background side. In this case, only occlusion and shading cues support the user.

9.4 Applications of VSS

In the field, VSS can aid surgery planning and risk analysis tasks. Judging distances between tumors and vital vessel structures in its close proximity is important to avoid dangerous situations for surgeons later on. The assessment of rib cage data sets is also suited for our technique.

Injury avoidance in vivo operations is another application of VSS, e.g. the analysis of needle placements, or targeting tasks for radiofrequency tumor ablation in which a probe has to be placed inside the tumor without damaging surrounding structures.

The expert, interviewed in Section 8, mentioned guidewire insertion during catheter placement to obtain safe access to blood vessels. For this procedure it has to be known how to bend the guidewire a priori to ensure that it follows the right path in the vessel's lumen to its destination, a narrowing for example. A distinct view on the vessels' geometry can be more advantageous by using VSS as depth cue.

10 Conclusions and Future Work

Within this paper we have presented VSS, a novel technique to visualize complex vascular structures. VSS has been developed with our proposed vessel visualization design goals in mind, such that they communicate shape and depth while still allowing for the communication of functional parameters without requiring instrumentation of the user. It works on static images, such as frequently used in medical reports, and does not require explanations to be interpretable. After introducing the computation of VSS, we have discussed the importance of depth anchoring, which enables the association of void space surfaces and vessel trees. We have further shown how well-known depth enhancement techniques can be combined with VSS, serving as a canvas for these techniques. In addition, we could show that the technical realization of VSS is simple. Even that they can be carried out on the GPU in order to achieve interactive frame rates. The results of two user studies conducted with a total of 38 participants indicate that VSS helps to improve the depth perception of complex vascular structures by still supporting the visualization of functional parameters overlaid over the vessel's geometry. Similar observations have been made by an independent senior doctor. To our knowledge VSS, is the first vessel visualization technique, that has these capabilities.

In the future, we plan to further investigate which set of parameters works best for VSS to achieve maximum performance in depth enhancement. Eye tracking can therefore be used to analyze if VSS can function as passive cue. Furthermore, we are considering to utilize VSS to communicate further information, such as functional parameters or external text labels. We expect that it can benefit when combining such information with a pure iso-line depth enhancement. We are also interested in investigating how much void space is actually needed to be useful for the user. Lastly, we would like to study the effect of not using illumination on the vessels' surface, being thus VSS the only depth cue in the image. When having such knowledge, it would become possible to predict for which other geometric structures VSS might be beneficial.

While the proposed pipeline is able to interactively generate and visualize VSS, there is still room for improvement. For example, the detection of contours and their hierarchical classification could also be parallelized on the GPU, which, we believe, will even further increase the performance of VSS.

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