Eurographics Workshop on Visual Computing for Biology and Medicine (2017)
S. Bruckner, A. Hennemuth, and B. Kainz (Editors)

Combining Pseudo Chroma Depth Enhancement and Parameter Mapping for Vascular Surface Models

B. Behrendt[1] & P. Berg[2] & B. Preim[1] & S. Saalfeld[1]

[1]Dept. of Simulation and Graphics, University of Magdeburg, Germany
[2]Dept. of Fluid Dynamics and Technical Flows, University of Magdeburg, Germany

Abstract

The presence of depth cues in a visualization can be a great aid in understanding the structure and topology of a vessel tree. Pseudo Chromadepth is a well-known technique for enhancing depth perception in vascular 3D models. Since it strongly relies on the color channel to convey its depth cues, it is traditionally not suited for combined visualizations comprising color-encoded surface parameters.
In this paper, we present and evaluate the use of a modified form of Pseudo Chromadepth that supports displaying additional surface parameters using the color channel while still increasing depth perception. This technique has been designed for the visualization of cerebral aneurysm models. We have combined a discretized color scale to visualize the surface parameter with the Pseudo Chromadepth color scale to convey depth using a Fresnel-inspired blending mask.
To evaluate our approach, we have conducted two consecutive studies. The first was performed with 104 participants from the general public and the second with eleven experts in the fields of medical engineering and flow simulation. These studies show that Pseudo Chromadepth can be used in conjunction with color-encoded surface attributes to support depth perception as long as the color scale is chosen appropriately.

Categories and Subject Descriptors (according to ACM CCS): I.3.7 [Computer Graphics]: Three-Dimensional Graphics and Realism—Color, shading, shadowing, and texture I.4.8 [Image Processing and Computer Vision]: Scene Analysis—Depth cues

1. Introduction

A large set of vessel visualization techniques have been developed, including surface and volume rendering, illustrative techniques and model-based techniques. Some of these techniques are carefully adapted to shape or depth perception by using special color scales [PBC*16]. The downside of relying on color scales to convey depth is that they often prevent the color channel from being used to visualize parameters on the vessel wall.

Studying vascular diseases, such as plaques and abdominal or cerebral aneurysms, involves the evaluation of both morphology and hemodynamic parameters. Morphologic parameters of objects can usually be directly inferred from the visualization (such as the position in the vessel tree) or determined by using measuring tools (such as size or aspect ratio). Hemodynamic parameters are either measured or derived with a computational fluid dynamic simulation and either conveyed in the form of stream or path lines (to display blood flow patterns) or by mapping information directly onto the vessel surface using a color scale (such as pressure or wall shear stress). Using colors to encode the information onto the vessel surface is a common technique and well accepted by physicians.

In this paper, we will examine if this type of encoding can be combined with additional visualization techniques to increase depth perception. We present a framework for the improved visualization of vessels that features enhanced depth perception in addition to allowing surface parameters to be mapped to the vessel wall using color scales. Our approach uses different color scales on the vessel surface to create separate visualizations for depth and surface parameters, which are then combined using a blending mask. The generation of this mask is inspired by the Fresnel effect, which describes the reflection of a surface based on the viewing angle.

An important application for such a technique is supporting the understanding of cerebral aneurysms. Cerebral aneurysms show a high prevalence in the western population (3-5 %) [BSB06], while their annual risk of rupture is below 1 % [MKH*12]. On the one hand, the bleeding caused by a rupture can have fatal consequences. On the other hand, the treatment procedure itself is risky and can lead to severe complications. Especially in the case of small, asymptomatic cerebral aneurysms, the mortality rate of the treatment may exceed the risk of rupture [Wie03].

Therefore it is vital to assess its risk of rupture to devise an optimal, patient-specific treatment plan. This is especially true for patients with multiple aneurysms that may require several treatment sessions. Each aneurysm has its own individual risk of rupture, and each separate treatment session increases the overall procedural risk. To minimize the risk of both treatment and incidence of a rupture, the physicians need to identify and treat the aneurysms with the highest risk of rupture and keep the rest under observation.

2. Related Works

There are various ways to enhance the perception of both depth and shape in computer-generated 3D images [BCFW08, PBC*16]. In this paper, we focus on the use of color to increase the perception of depth.

Rheingans and Ebert used distance color blending, a combination of intensity depth cueing and color modulation, to increase depth perception in volume models [RE01]. This approach mimics the light-scattering effect of the atmosphere by reducing color intensity of more distant objects and adding a slightly blue tint to them. Joshi et al. later validated this method specifically for enhancing depth perception in vessel visualization [JQD*08].

Another method to convey depth by emulating real-world optical effects is depth of field (DoF), where objects are gradually blurred depending on their distance to a focal plane. Without using eye tracking, this focal plane needs to be positioned manually or using heuristics [RSH06]. Grosset et al. evaluated the effectiveness of various DoF techniques in a study with 25 participants [GSBH13]. They found that DoF only supports depth perception when the focal plane is placed in the front of the scene. A general problem of DoF is that it is not possible to focus on two objects at the same time unless they have a similar distance to the viewer.

Ritter et al. employed hatching to visualize depth relations in complex vascular structures [RHD*06]. Whenever two sections of the anatomy were overlapping, the posterior structure was hatched to simulate a shadow. The size of the hatched area directly corresponded to the distance between the two structures. In a study with 160 participants, Ritter et al. were able to show that their approach significantly increased depth perception when compared to Gouraud shading. Lawonn et al. presented a combination of depth-dependent halos, support lines and the illustrative shadows by Ritter et al. to improve perceptibility of depth [LLPH15]. These support lines are cast from manually selected points of the vessel onto a plane, creating an effect similar to beams holding the model up. They could successfully convey the depth of a complex 3D model in a static 2D image, although it does not allow for a free rotation of the vessel.

Pseudo Chromadepth (PCD) was introduced by Ropinski et al. [RSH06]. It is based on the idea of enhancing depth perception in 3D visualizations of angiography datasets by mapping the depth of each point on the surface to a color gradient. PCD was derived from the chromadepth technique [Ste87], which follows a similar idea. Due to the fact that light with different wavelengths is refracted at different angles in the lens of the eye, color can be used to create the illusion of depth in an otherwise flat image. This does not necessarily require any special type of surface, glasses or other additional devices, although the effect can be strongly enhanced by diffraction grating glasses [BC98].

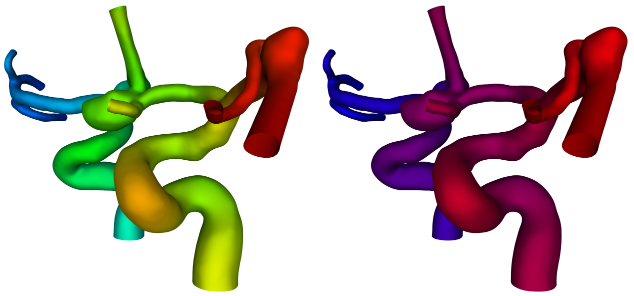

Figure 1: *Comparison of the chromadepth (left) and pseudo chromadepth (right) color scales applied to a cerebral vessel.*

Instead of using the full range of colors visible to the human eye, Pseudo Chromadepth only uses a gradient from red (low depth) to blue (high depth). A wide range of hues might distract from the shading used to convey shape. The chroma depth color scale may work well for geometric objects or shapes with low complexity, such as an organ surface, but it is inappropriate for such complex shapes as vessels. A comparison between both techniques can be seen in Figure 1.

The colors red and blue were chosen due to their high difference in wavelength to maximize their chromadepth effect. Additionally, red is attention-grabbing and intuitively perceived as foreground, whereas blue – the color of the sky – is perceived as background. In a study with 14 participants, Ropinski at al. showed that angiography images could benefit from color-encoded depth information [RSH06]. Additional studies confirmed this effect [KOCC14].

The Fresnel effect has previously been used to integrate additional information into vessel visualizations. Gasteiger et al. introduced Ghosted Views, which use an approximation of the Fresnel effect to modulate the opacity of vessel surfaces [GNKP10]. This method allows to show the blood flow inside of a vessel without removing the entire front-facing part of the surface, thus increasing shape perception of the vessel. In a subsequent study, Baer et al. showed that this approach allowed for a more accurate analysis of the aneurysm and its flow patterns [BGCP11]. Glaßer et al. presented a similar technique, which uses the Fresnel effect to highlight vessel boundaries [GSB*16]. They also used discrete color scales to visualize surface attributes on the vessel surface, but did not combine this directly with their boundary-enhanced view.

3. Method

The idea of both chromadepth and PCD is based on the fact that the color channel of the image does not contain any relevant information and can therefore be fully utilized to increase depth perception [RSH06]. While this is true for angiography images, it cannot be generalized for any kind of medical visualization task.

When analyzing vascular pathologies, physicians are often interested not only in the vessel shape, but also in functional parameters, such as pressure or wall shear stress on the vessel wall. An appropriate visualization should therefore convey the general shape and depth of the vessel model, but simultaneously encode the aforementioned functional parameters as well. The physician should be able

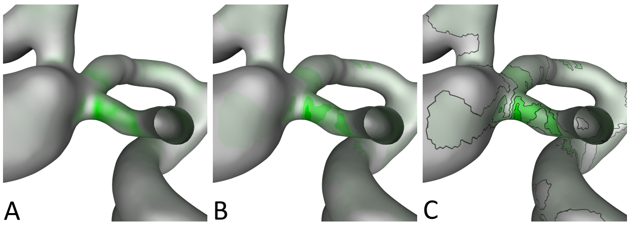

Figure 2: *Comparison of a smooth color scale (A), discrete color scale (B) and discrete color scale with additional boundaries (C) when visualizing wall shear stress on a vessel.*

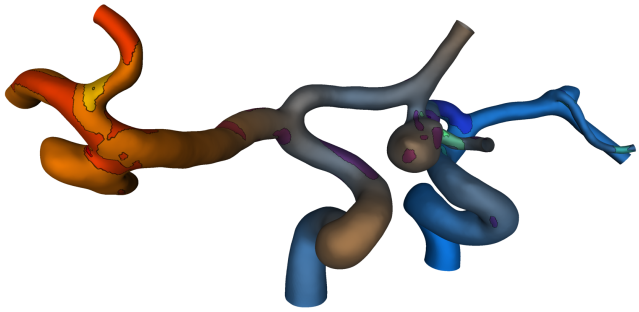

Figure 3: *PCD shading where the depth is continuously mapped to the red and blue color scale and the scalar parameter is mapped to the green color channel using a discrete scale.*

to compare different regions on the vessel wall regarding their spatial relation and parameter values without having to switch between different types of shading.

These requirements prevent the application of traditional chromadepth or PCD shading, as it would conflict with the parameter information encoded into the color channel. A likely result would be a slower analysis with increased risk of errors and mental load for the physician. In contrast, we present a technique that allows the use of PCD in addition to mapping data to the surface color of a model, which is described in the following.

3.1. Surface Visualization

The vessel surface models are generated from 3D digital subtraction angiography data with cerebral aneurysms by applying a threshold-based segmentation. The iso-surface is extracted and converted into a triangle mesh. This mesh is then visualized as a 3D surface model and illuminated using Phong Shading with a single headlight.

For the extraction of hemodynamic parameters, such as pressure and wall shear stress, the surface mesh is employed for computational fluid dynamic simulations. We realized two approaches: the parameters are mapped to a color scale ranging from white to orange for a pilot study and to a color scale from white to green for the final study. We decided against using hatching to convey the additional information, as it may also interfere with the Phong-based lighting we use to convey the shape of the vessels. Furthermore, hatching is not well suited to highlight small areas of interest.

When analyzing surface parameters on a vessel, physicians often look for "hot spots". These are small areas with very high values, which can be perceived pre-attentively when they are encoded with color. To highlight regions with particularly high or low parameter values, we have chosen to discretize the color scale to five different shades (Fig. 2B). To make these shades even more distinct, a black outline has been added to mark the transition line between shades (Fig. 2C).

3.2. Fresnel-Inspired PCD

Traditionally, PCD occupies the entire color channel. This mostly prevents additional information from being shown on the objects surface. Since the green color channel is not occupied by PCD, a trivial solution would be to map information to that specific color channel only. Such a visualization (Fig. 3) would be unsatisfactory, since it is very difficult for humans to mentally disassemble a color into their respective channels. The same parameter value can have widely different hues depending on its location on the model's surface. As a result, the interpretation of such a visualization is very challenging.

Our method displays the PCD color scale on the edges of the 3D model only, based on the current viewing direction. This type of shading is inspired by the Fresnel effect, which describes the amount of reflection and refraction of light on a surface in relation to the viewing angle. A flatter viewing angle on a surface increases the amount of light that is reflected, resulting in the surface appearing brighter when lighted (Fig. 4A).

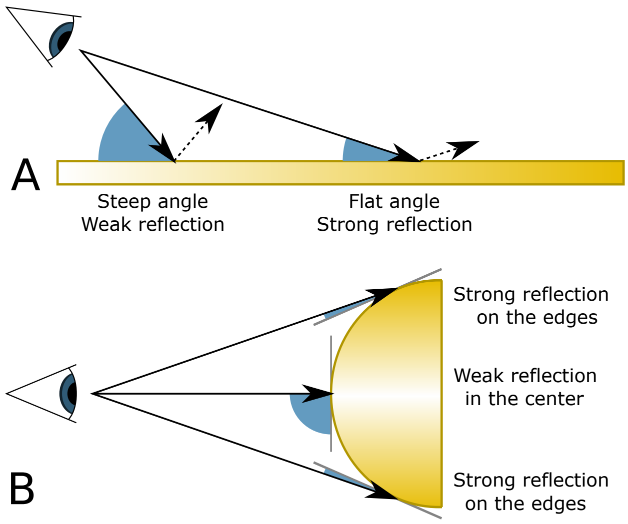

Figure 4: *Principle of the Fresnel effect; the amount of reflection on a reflective surface depends on the viewing angle (A). When applied to spherical object; the edges exhibit strong reflections due to the shallow viewing angle (B).*

A physically accurate calculation of this effect is quite complicated, especially when taking into consideration that due to chromatic dispersion, the strength of the Fresnel effect also depends on the light components' wavelengths. Instead, we use a simplified version of this effect to generate a mask for overlaying the PCD color gradient. Our Fresnel-Inspired PCD (FI-PCD) mask M_{PCD} is calculated similarly to ghosted views [GNKP10] using the following formula:

$$M_{PCD} = f_{scale} * (1 - |2 * \frac{\arccos(\vec{I} \cdot \vec{N})}{\pi} - 1|)^s$$

$\vec{I}$ and $\vec{N}$ are the incident and normal vectors at the surface respectively. The scaling factor f_{scale} can be used to adjust the effect strength. Similarly, the variable s controls the steepness of the transition from surface to PCD scale. In our application, we have empirically chosen a scaling factor of 1 and a steepness of 2.

M_{PCD} is dependent on the angle between the normal and incident vectors, reaching its maximal value when they are orthogonal to each other. On spherical or tubular models, the Fresnel effect strongly increases the reflectiveness around the edges of the model (Fig. 4B).

Our final FI-PCD visualization comprises two different images, both of them renderings of the vessel surface. The first one has the parameters mapped to its color (Fig. 5A), the second is colored entirely according to the PCD scale (Fig. 5B). For each pixel in the final image, the pixel's value in the mask M_{PCD} is extracted and used as weight for the linear interpolation between the two images (Fig. 5C). For example, black M_{PCD} pixels yield the color-coded parameter value and white M_{PCD} pixels yield the PCD-based color-coding.

The resulting FI-PCD visualization (Fig. 5D) allows mapping a scalar parameter to any color scale, while PCD depth cues are shown only on the edges of the model. They are still clearly visible to the user while interference with the object's surface color is reduced. Usually, the physician would rotate the vessel in a way that the interesting areas are facing the camera instead of being relegated to the edge of the model. In addition to providing depth cues by hue, displaying the PCD scale at the edges also increases the perceptibility of overlaps, which is another important depth cue.

3.3. Implementation

Generation and composition of both images is performed mostly in the fragment shader.

When rendering the surface, the attribute values for the surface are sent to the graphics card as vertex attributes. Additionally, the highest and lowest values of the attribute as well as the highest and lowest depth values from the previously rendered frame are stored in the fragment shader as uniform variables. Then, the attributes are interpolated between vertices, normalized to a $[0,1]$ range and transformed into a color value by the fragment shader. The transformation is performed linearly in RGB color space between white (*#ffffff*) and orange (*#ff7f00*, pilot study) or green (*#00ff00*, final study). Next, the resulting color value is discretized into five distinct shades and used as surface color.

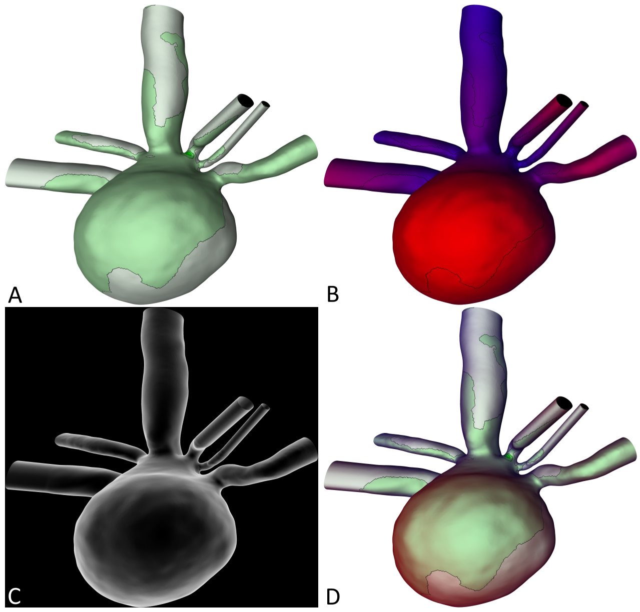

Figure 5: *Composition of images to create the FI-PCD visualization: Surface color image (A), PCD image (B), Composition mask (C) and resulting FI-PCD image (D).*

The boundaries between color shades are generated dynamically on a per-triangle base by analyzing the affinity of each vertex to a certain color class. For each triangle with different affinities at the edges, the fragment shader draws a black line separating these vertices. This approach allows for a very fast generation of dynamic outlines on the surface, without the need for any pre-processing or the creation of new geometry. Unfortunately, since the lines are always at the center between two vertices, they do not always line up exactly with the actual color transition. On a model with a decent triangle resolution, this effect is only noticeable when zooming in very closely to the surface.

The second image is generated by normalizing the current fragment's depth using the previously stored depth range and mapping the resulting value to the PCD color scale. Using the depth range from the previous frame allows us to draw the geometry using a single rendering pass, although it produces a barely noticeable flicker in the PCD color scale during fast animations. Afterwards, the M_{PCD} value is calculated and used to compute the composition of both images.

4. Evaluation

Our evaluation consists of two separate studies; a pilot study with participants from the general public, and a final study with experts in the fields of medical engineering and flow simulation. All participants were shown 3D visualizations of intra-cranial vessel surfaces models. These models had one of multiple available attributes mapped to their surface, such as pressure or wall shear stress. Participants were shown two points on these datasets and had to select either the one closest to them or the one with the highest parameter.

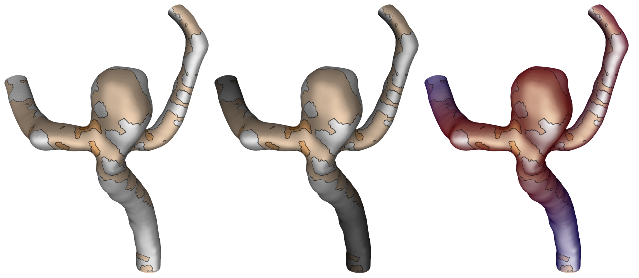

Figure 6: *The different shadings used in the first study: No depth cues, trivial brightness cues and FI-PCD (f.l.t.r.)*

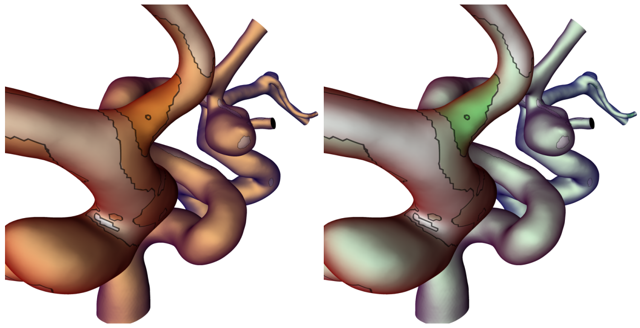

Figure 7: *Different color scales used in the first (left) and second (right) study in combination with FI-PCD.*

The datasets were shown with three different shading styles. The first style was a normal, phong-shaded visualization without any distinct depth enhancement. The second used brightness as a depth cue. Distant triangles were reduced in brightness, with the highest possible reduction being 75%. This value was chosen empirically as a trade-off between having a strong effect on depth perception while still being able to discern the color of farther away parts of the model. The last style was our implementation of FI-PCD. All three visualization styles can be seen in Figure 6.

We expected the visualization without depth cues to perform worst in the depth judgment, but best in the parameter judgment task. As both brightness-based cues and FI-PCD would partially overlay the surface color scale, we expected them to perform equally well, but not as good as the visualization without depth cues. Since PCD has proven superior to brightness- or contrast-based cues by studies in the past (such as [KOCC14]), we expected FI-PCD to perform best in the depth judgment task.

The pilot study allowed us to identify several flaws in our technique. Before the final study, we corrected these problems by changing some aspects of both our visualization as well as the application. First, the color scale used to encode the surface attribute was changed from white-to-orange to white-to-green. The original orange scale was chosen due to aesthetic reasons. However, many participants in the pilot study noted that red areas from the FI-PCD shading interfered with orange areas from the surface attribute color scale. Since PCD only uses the red and blue color channel, green was chosen for the surface attribute to prevent color overlaps. A comparison between the two color scales in combination with FI-PCD can be seen in Figure 7.

We also added a permanent legend for the used color scales in the bottom left corner of the screen. This was done in response to some participants in the first study confusing the meaning of some of the colors during the course of the study. The legend always encoded the surface attribute color scale in combination with the current depth enhancement color scale. All three scales can be seen in Figure 8.

4.1. Application

When started, the test application presents the user with a few instructional pages. All of them include a "Continue"-button that becomes enabled after five seconds and allows the participant to advance to the next screen. The first and second pages contain general information about the study as well as labeled example images for all types of visualizations used in this study, as seen in Figure 9. To prevent any bias, these images are always shown in a random order.

The actual study consists of two blocks, where the user has to select either the point closest to them, or the one with the highest scalar surface parameter. Therefore, the user has to identify the spatial relation or ranking of scalar values of two selected points on the surface (Fig. 10). Additionally, they always have the option to click a button labeled "Not sure" if they cannot decide for one of the points. During each task, the application measures the completion time, rotation time and whether the user clicked the correct point or hit the "Not sure"-button instead. For the rotation time, we counted the amounts of single frames that a rotation was performed in and converted them to a duration in seconds. Frames where the user kept the left mouse button pressed without moving the mouse (therefore not actually performing a rotation) were not included.

Each block is introduced by another instructional page, which is then followed by six dedicated tutorial datasets. They serve as a way to familiarize the user with the visualizations and tasks, therefore their measurements are excluded from the final statistic. Furthermore, a learning effect during the actual evaluation is prevented.

After completing the tutorial for each block, the user sees a message explaining that the training part is over and asking them if they have any questions before proceeding. This was done to ensure they were properly prepared and did not have to ask questions during the time-measured evaluation. They were encouraged to complete

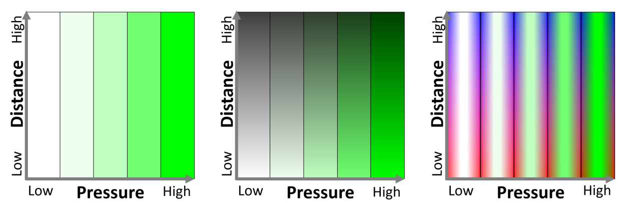

Figure 8: *The color scale legends shown in the final study: No depth cues, trivial brightness cures and FI-PCD (f.l.t.r.)*

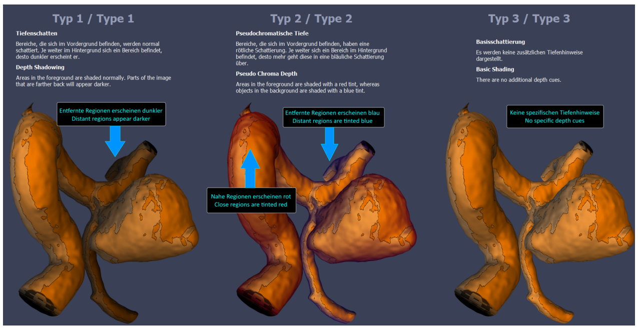

Figure 9: *Instructional page detailing the different visualizations (ordered randomly). For the second study, the images were updated to reflect the changed surface color scale.*

Figure 11: *Experimental setup for the pilot study. The two disabled monitors in the corner were not part of the study.*

each task as fast and accurately as possible due to the time measurement. "Guessing" the correct answer was discouraged in favor of using the "Not sure"-button.

The order of blocks was consistent for all participants, starting with the depth judgment tasks and then switching over to the parameter judgment task. Each task consisted of 30 images in total, six of them being the training images. All users were shown the same images, although they were ordered randomly. The application ensured that the same dataset did not appear twice in a row. The participants did not receive any immediate feedback about the correctness of their answers during the study, but statistics about their general performance were made available to them afterwards upon request.

4.2. Questionnaire

After completing the assignments on the computer, all participants were asked to fill out a questionnaire. In addition to age, biological gender and known visual disorders, participants were asked if they have experience with analyzing medical data or modeling 3D objects and whether they play 3D video games regularly. For visual disorders, we were mostly interested in those that impede the ability to perceive color or depth. Since there are many cases where people are unaware of their color perception impairment, we added a very abbreviated color blindness test using three Ishihara plates. Two of them had numbers encoded in them (42 and 6) while the last one did not. None of the participants that had not already denoted a form of color blindness in the questionnaire failed this test.

At the end, participants were asked to rank the three types of visualizations according to their usefulness for perceiving depth and the surface attribute as well as their general aesthetic. They were also given space for any additional remarks.

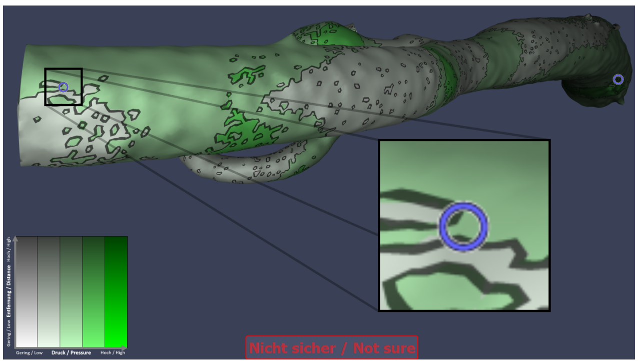

Figure 10: *One of the datasets with two marked points shown to the participants as part of the depth judgment task. The image used brightness-based depth cues and the green color scale from the final study.*

5. Pilot Study

For the pilot study, we took advantage of the popular open house day at our university as a means of finding volunteers. Visitors of this event were asked to participate in our study. Both verbal explanations as well as written instructions and other materials were made available to the participants.

Half of the participants were randomly selected to be given limited control over the camera during the study, whereas they can rotate the dataset by ten degrees in any direction. These participants were shown an extra paragraph in one of the instructional pages of the application explaining that they had the ability to orbit the camera. If they did not rotate the camera at least once during the tutorial, they were reminded by a pop-up dialog.

5.1. Participants

A total number of 104 people from the general public volunteered to participate in the pilot study. Ten of them were later rejected due to vision impairments (i.e. various forms of color blindness or problems with depth perception), failing to comprehend the assignment or not filling out the corresponding questionnaire. The age of the participants ranges from 11 to 73, with an average of 28.6 and a standard deviation of 14. Out of the 94 participants that were included in the evaluation, 40 were female (42.6 %).

5.2. Setup

In order to allow for a high number of participants, we set up four PCs for simultaneous use (Fig. 11). They were positioned in a corner of the room to prevent distractions from the rest of the event. To ensure comparability of the results between the different stations, we used PCs with similar hardware specifications and identical screens. All stations ran the application at a resolution of 1920 × 1080 with 60 frames per second.

The participants were given a short verbal introduction about the topic of vessel visualization in general and the study in particular. To keep any descriptions simple and explanations short, the different scalar attributes shown in the visualizations were always just referred to as "pressure" despite also including wall shear stress. After that, they were instructed to sit down at one of the stations and follow the on-screen instructions from the application.

5.3. Results

For each participant, we calculated four values from our measurement for each shading style. *Correctness* is the percentage of correct answers, e.g. how often participants selected the nearest point (during the depth judgment task) or the point with higher scalar value (during the parameter judgment task), respectively. *Certainty* denotes the percentage of answers where the user selected any of the points and not the "Not sure"-button. *Duration* is the average time in seconds the users took for each image. *Rotation* is the average time the user spend rotating the dataset. For this value, we only included users who actually rotated the dataset.

The ability of the participants to pick the point closest to them benefited from having any form of depth cues enabled (Fig. 12). Without them, they were only correct in 79 % of the depth judgment tasks. Brightness-based depth cues increased their accuracy to 90 %, whereas FI-PCD only increased it to 85 %. This is surprising, as we were expecting the FI-PCD to provide much better depth cues than the brightness-based approach.

Although being reminded after each training session that they could rotate, only 35 of the 50 users with the ability to rotate actually made use of it. Three of them performed so little rotation that we assume that to be accidental. This was possibly a result of being overwhelmed due to unfamiliarity with 3D visualizations. Users that stated experience in 3D modeling or 3D video games rotated for an average of 0.3 seconds per dataset, whereas users with no experience only rotated for 0.19 seconds.

The values for certainty and rotation are extremely similar for each of the three shading styles. The users generally rarely used the "Not sure"-button in this study. The average duration was slightly higher for the visualization without depth cues (4.2 s) in comparison to brightness-based cues (3.8 s) and FI-PCD (4.0 s).

For the parameter judgment task, the visualization without cues reached the best average correctness (96 %, Fig. 13). Users also performed fastest, with an average duration of 2.9 s per image. This result was to be expected, as there are no additional color or brightness gradients added to the surface color. The brightness-based depth cues performed better than FI-PCD in regards to correctness (92 % compared to 80 %) and duration (3.2 s compared to 3.5 s).

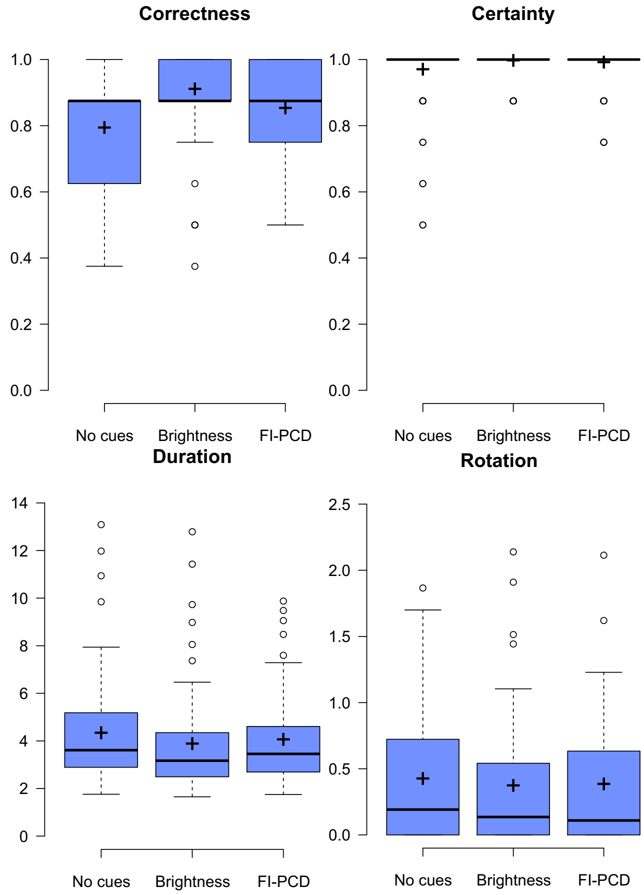

Figure 12: *Box plots showing correctness (top left), certainty (top right), duration in seconds (bottom left) and rotation duration in seconds (bottom right) for the depth judgment task over all participants from the pilot study.*

This most likely stems from our choice of color scale to encode the surface parameters in this study. Many participants remarked that the orange from the surface color scale was interfering with the red from the PCD scale, thus making it hard to distinguish them.

Interestingly, in order to interpret the colors of areas strongly affected by depth cues (i.e. those close to the edge of the vessel when using FI-PCD or those in the background when using brightness cues), users often resorted to "counting" color gradients. They would search for an area that was completely white and then count the boundaries they had to cross to reach the marked point. That way, they could tell which area represented a higher parameter value even without being able to distinguish the colors directly. Since this approach requires a visually uninterrupted path from a marked point to a white area, it was not possible in all cases.

Just as in the depth judgment task, the certainty for all shading styles is very similar. Rotation was used even more rarely in this task. Since the marked points were never obstructed by other geometry, there was little point in rotating the dataset to compare the surface coloring.

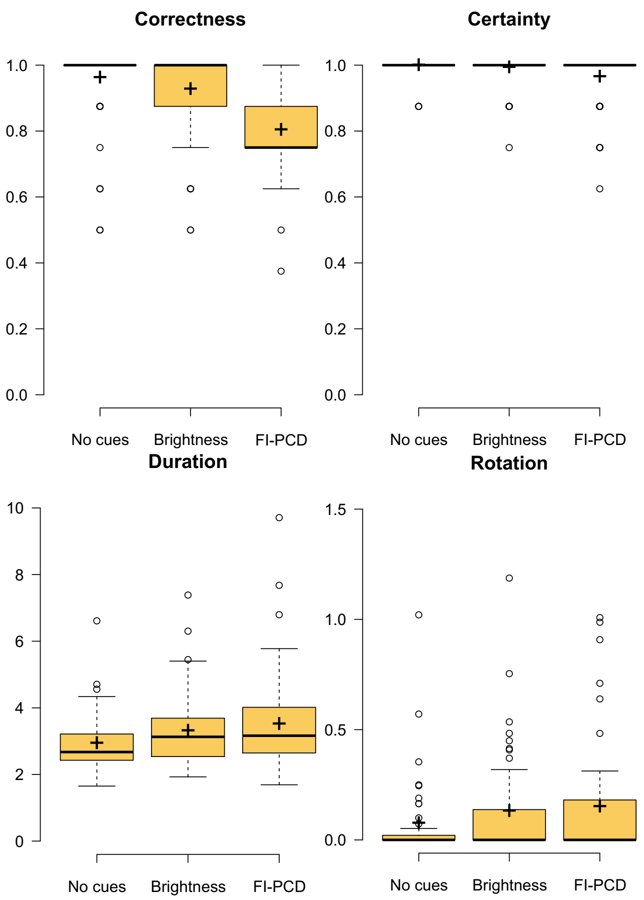

Figure 13: *Box plots showing correctness (top left), certainty (top right), duration in seconds (bottom left) and rotation duration in seconds (bottom right) for the parameter judgment task over all participants from the pilot study.*

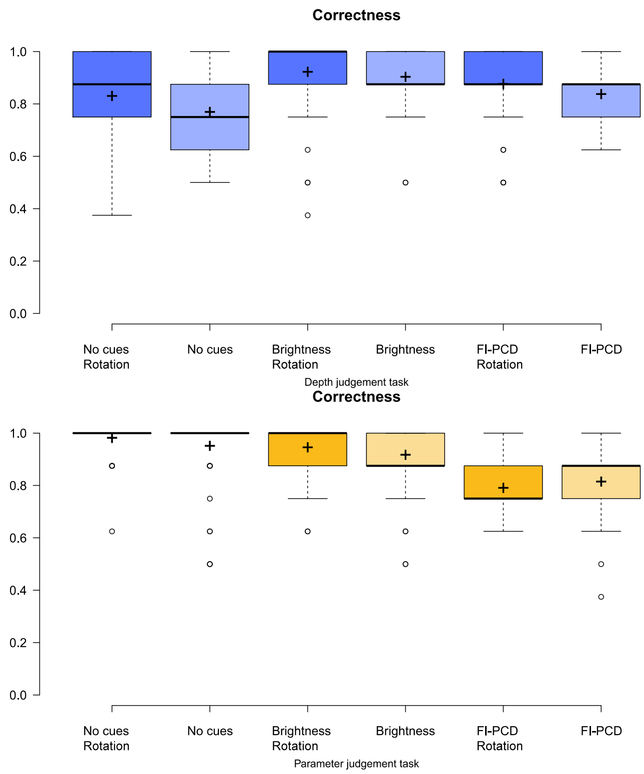

Figure 14: *Influence of rotation on the ability to judge depth (top) and surface parameters (bottom)*

We also analyzed the correctness in regards to whether the users made use of rotation during the tasks. The ability to rotate the view had very little effect on the results of the surface parameter task (Fig. 14, bottom). The correctness of the depth judgment task increased when rotation was used on the FI-PCD images as well as those without depth cues. Since parallax movement is another important depth cue, this improvement is not surprising.

6. Final Study

For the final study, we directly approached several experts in the fields of medical engineering and flow simulation. Due to the lower number of participants in this study, we decided against splitting them into two groups. Therefore, we allowed all of them to rotate the camera.

6.1. Participants

Eleven experts volunteered to take part in our final study. One person was excluded due to color blindness. The age of the included participants ranged between 22 and 41 (average of 29.1), with two of them being female (20 %).

6.2. Setup

The second study was performed on a laptop, as it took place at our participant's workplace. Despite having less powerful hardware than the PCs used in the first study, it was still able to run the application at 1920 × 1080 with 60 frames per second.

For this study, the introduction to vessel visualization was either omitted or kept very brief, since most participants were familiar with this field already. The instructions given by the application itself remained unchanged from the pilot study.

6.3. Results

In our second study, the FI-PCD method reached better results (Fig. 15). During the depth judgment task, users were able to pick the correct point in 94 % of the cases. With the brightness-based shading, they were able to choose correctly in 90 % of the cases. Without any depth cues, the participants only reached 85 % accuracy.

The same trend is visible in the certainty plots. Overall, the duration and rotation plots from the second study show the same trends as those in the first study. Interestingly, users took longer for their decision and also rotated the view more when viewing the datasets with FI-PCD compared to brightness-based depth cues. This may be due to the fact that the combination of PCD and surface color scale can no longer be pre-attentively perceived.

As expected, users were able to judge the parameters best when no depth cues were present, reaching a mean correctness of 98 %. Brightness-based depth cues produced an almost identical result with a mean correctness of 96 %. FI-PCD shading had the strongest negative effect on the participant's ability to compare parameter values on the surface, although not as strong as in the first study. The mean correctness in this case was 90 %.

The average duration for each decision (from both tasks) was significantly higher in the second study (5.5 s) compared to the first (3.7 s). Similarly, the average rotation duration was also higher (0.3s compared to 0.2 s). This may indicate that in the second study, participants put more effort into the evaluation.

7. Discussion

Our studies have shown that FI-PCD can increase the perception of depth while maintaining recognizability of surface scales on the vessel surface. For the latter, a careful choice of color scale is required to avoid conflicts with the color gradients introduced by PCD. In our first study, we used an inappropriate color scale to encode surface parameters. This strongly reduced our method's ability to convey both depth and surface parameters. We were able to remedy this problem in the second study by choosing a different scale that relies only on the green color channel, which goes unused by PCD. This resulted in a higher increase of depth perception than classic, brightness-based depth cues.

We decided to use a discretized color scale instead of a smooth one. This reduces ambiguity between the surface color and PCD scale while at the same time highlights areas with high or low values, which physicians are often interested in since their decisions are discrete as well. The highlighting was increased further by the introduction of outlines around the differently colored surface regions. This created a robust visualization that still allowed users to compare parameter values on the surface even when overlaid with another color or brightness gradient.

Both studies showed that overlaying the color channel with depth

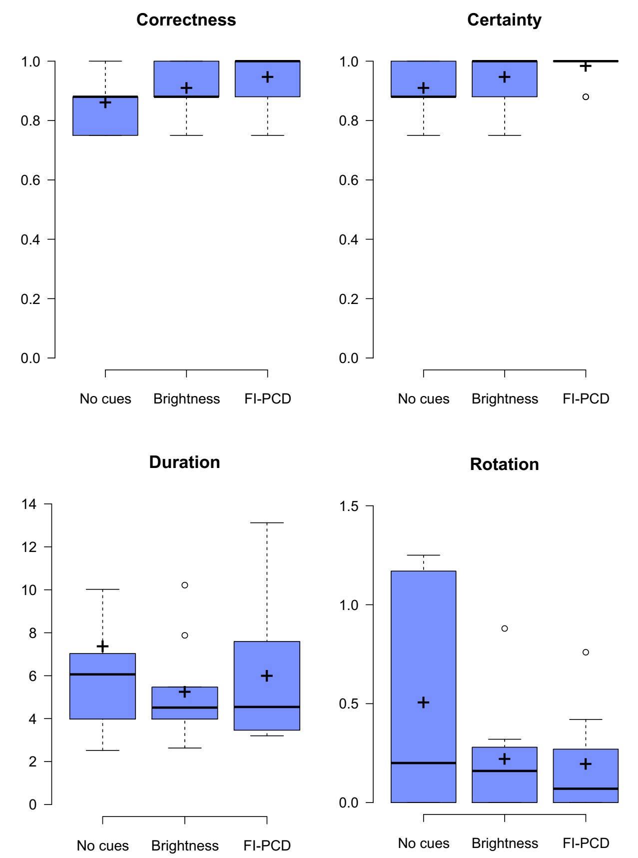

Figure 15: *Box plots showing correctness (top left), certainty (top right), duration in seconds (bottom left) and rotation duration in seconds (bottom right) for the depth judgment task over all participants from the final study.*

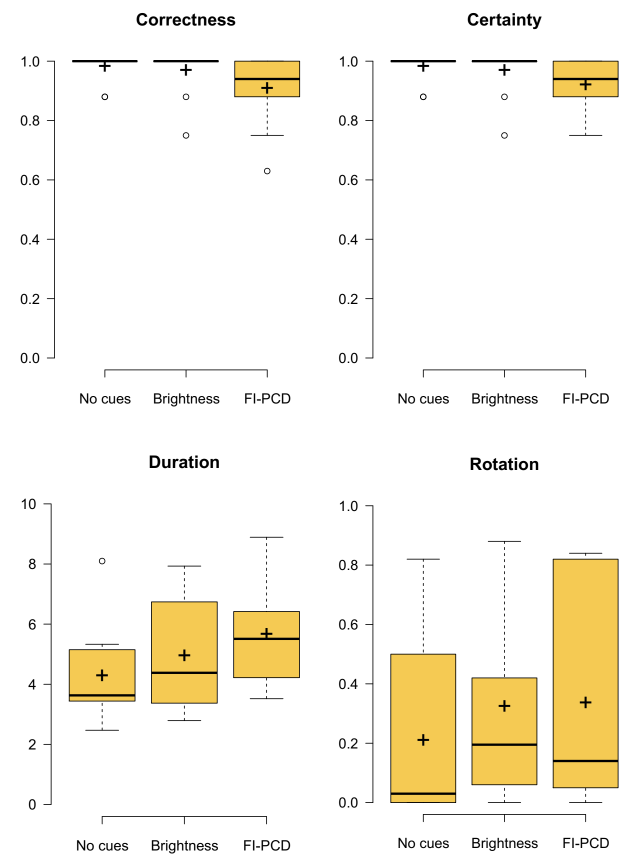

Figure 16: *Box plots showing correctness (top left), certainty (top right), duration in seconds (bottom left) and rotation duration in seconds (bottom right) for the parameter judgment task over all participants from the final study.*

cues reduces the recognizability of the surface color scale. This effect was strongest when using FI-PCD. A likely explanation is that FI-PCD affects the color of both close and distant regions, whereas brightness-based depth cues only affect distant regions. Therefore, FI-PCD should be kept as an optional addition to any visualization that can be disabled in case an in-depth comparison between the scalar values of different surface points is required.

8. Conclusion & Future Work

With FI-PCD, we have introduced a novel rendering technique that combines Pseudo Chromadepth with color-encoded surface attributes to visualize vascular anatomy in combination with scalar parameters. We have performed two studies to evaluate our technique. While we could show that FI-PCD can enhance the perception of depth, there are still issues that need to be improved on.

First, FI-PCD tends to distort the underlying color scale. This can be partly remedied by choosing a scale that does not interfere with the red and blue colors from PCD, such as our white-to-green scale. However, it would be interesting to see if this effect can be further reduced by using different values for the scaling factor and steepness in our FI-PCD formula. Reducing the scaling factor or increasing the steepness would make the PCD color scale less prominent in the visualization. Therefore, it may be possible to find a setting that results in a better trade-off between depth and surface color perception.

In many scenarios, the physician would not only be interested in a surface parameter, but also blood flow patterns. Simply displaying them inside of the vessel anatomy using established smart visibility techniques would likely produce unsatisfactory results. In addition to having to cut or fade away parts of the surface to reveal the underlying flow (thus making it harder to see the surface color), displaying path lines with their own color scale would also add another layer of complexity to the color channel. A seamless way of integrating flow visualization would therefore be a useful extension.

Acknowledgments

We would like to warmly thank Prof. Douglas W. Cunningham and Maria Lutz for their guidance and helpful remarks concerning the study design. Thanks also go to Patrick Saalfeld for his help with the statistical evaluation of our study results.

The work of this paper is funded by the European Regional Development Fund under the operation number 'ZS /2016/04/78123' as part of the initiative "Sachsen-Anhalt WISSENSCHAFT Schwerpunkte".

References

[BC98] BAILEY M., CLARK D.: Using ChromaDepth to Obtain Inexpensive Single-image Stereovision for Scientific Visualization. *Journal of Graphics Tools 3*, 3 (1998), 1–9. 2

[BCFW08] BARTZ D., CUNNINGHAM D. W., FISCHER J., WALLRAVEN C.: The Role of Perception for Computer Graphics. In *Eurographics (STARs)* (2008), pp. 59–80. 2

[BGCP11] BAER A., GASTEIGER R., CUNNINGHAM D., PREIM B.: Perceptual evaluation of ghosted view techniques for the exploration of vascular structures and embedded flow. In *Computer Graphics Forum* (2011), vol. 30, pp. 811–820. 2

[BSB06] BONNEVILLE F., SOUROUR N., BIONDI A.: Intracranial aneurysms: An overview. *Neuroimaging clinics of North America 16*, 3 (2006), 371–82, vii. 1

[GNKP10] GASTEIGER R., NEUGEBAUER M., KUBISCH C., PREIM B.: Adapted Surface Visualization of Cerebral Aneurysms with Embedded Blood Flow Information. In *VCBM* (2010), pp. 25–32. 2, 4

[GSB*16] GLASSER S., SAALFELD P., BERG P., MERTEN N., PREIM B.: How to Evaluate Medical Visualizations on the Example of 3D Aneurysm Surfaces. In *Eurographics Workshop on Visual Computing for Biology and Medicine* (2016). 2

[GSBH13] GROSSET A., SCHOTT M., BONNEAU G.-P., HANSEN C. D.: Evaluation of Depth of Field for depth perception in DVR. In *2013 IEEE Pacific Visualization Symposium (PacificVis)* (2013), IEEE, pp. 81–88. 2

[JQD*08] JOSHI A., QIAN X., DIONE D. P., BULSARA K. R., BREUER C. K., SINUSAS A. J., PAPADEMETRIS X.: Effective visualization of complex vascular structures using a non-parametric vessel detection method. *IEEE transactions on visualization and computer graphics 14*, 6 (2008), 1603–1610. 2

[KOCC14] KERSTEN-OERTEL M., CHEN S. J.-S., COLLINS D. L.: An evaluation of depth enhancing perceptual cues for vascular volume visualization in neurosurgery. *IEEE transactions on visualization and computer graphics 20*, 3 (2014), 391–403. 2, 5

[LLPH15] LAWONN K., LUZ M., PREIM B., HANSEN C.: Illustrative Visualization of Vascular Models for Static 2D Representations. In *Medical Image Computing and Computer-Assisted Intervention – MICCAI 2015*. 2015, pp. 399–406. 2

[MKH*12] MORITA A., KIRINO T., HASHI K., AOKI N., FUKUHARA S., HASHIMOTO N., NAKAYAMA T., SAKAI M., TERAMOTO A., TOMINARI S., YOSHIMOTO T.: The natural course of unruptured cerebral aneurysms in a Japanese cohort. *The New England journal of medicine 366*, 26 (2012), 2474–2482. 1

[PBC*16] PREIM B., BAER A., CUNNINGHAM D., ISENBERG T., ROPINSKI T.: A survey of perceptually motivated 3d visualization of medical image data. In *Computer Graphics Forum* (2016), vol. 35, pp. 501–525. 1, 2

[RE01] RHEINGANS P., EBERT D.: Volume illustration: Nonphotorealistic rendering of volume models. *IEEE transactions on visualization and computer graphics 7*, 3 (2001), 253–264. 2

[RHD*06] RITTER F., HANSEN C., DICKEN V., KONRAD O., PREIM B., PEITGEN H.-O.: Real-time illustration of vascular structures. *IEEE transactions on visualization and computer graphics 12*, 5 (2006), 877–884. 2

[RSH06] ROPINSKI T., STEINICKE F., HINRICHS K.: Visually Supporting Depth Perception in Angiography Imaging. In *Smart Graphics*, vol. 4073 of *Lecture Notes in Computer Science*. 2006, pp. 93–104. 2

[Ste87] STEENBLIK R. A.: The Chromostereoscopic Process: A Novel Single Image Stereoscopic Process. McAllister D. F., Robbins W. E., (Eds.), SPIE Proceedings, pp. 27–34. 2

[Wie03] WIEBERS D. O.: Unruptured intracranial aneurysms: Natural history, clinical outcome, and risks of surgical and endovascular treatment. *The Lancet 362*, 9378 (2003), 103–110. 1