Visually Supporting Depth Perception in Angiography Imaging

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Abstract. In this paper we propose interactive visualization techniques which support the spatial comprehension of angiogram images by emphasizing depth information and introducing combined depth cues. In particular, we propose a depth based color encoding, two variations of edge enhancement and the application of a modified depth of field effect in order to enhance depth perception of complex blood vessel systems. All proposed techniques have been developed to improve the human depth perception and have been adapted with special consideration of the spatial comprehension of blood vessel structures. To evaluate the presented techniques, we have conducted a user study, in which users had to accomplish certain depth perception tasks.

1 Introduction

In the past years medical imaging techniques have advanced and their application has become essential in medical diagnosis. Nowadays medical scanners allow to acquire high-resolution datasets at relatively low costs. Thus physicians can conduct examinations non-invasively and examine parts of the human body that otherwise would be not accessible. In many areas of medical imaging, 2D visualizations of the - in most cases inherently 3D - datasets are sufficient to communicate the desired information. Therefore medical images are traditionally viewed in 2D, as done for when instance examining x-ray images. 3D is exploited only in application areas where the depth information is essential to provide physicians insights. One of these application areas is angiography imaging used to examine abnormalities of blood vessel structures that usually have a complex 3D structure not easy to comprehend. An example of a cerebral vessel structure with an aneurism acquired through angiography is shown in Figure 1. Although the visualization techniques presented in this paper are applicable to any blood vessel dataset, we focus on cerebral vessel structures acquired through angiography.

Cerebral angiography is commonly used to detect significant stenosis as well as aneurisms. While stenosis are constrictions, aneurisms are expansions of a vessel arising from a too thin vessel membrane. Both stenosis as well as aneurisms cause an increased risk of stroke and must therefore be identified and treated early. There are several ways to treat detected abnormalities. The most common

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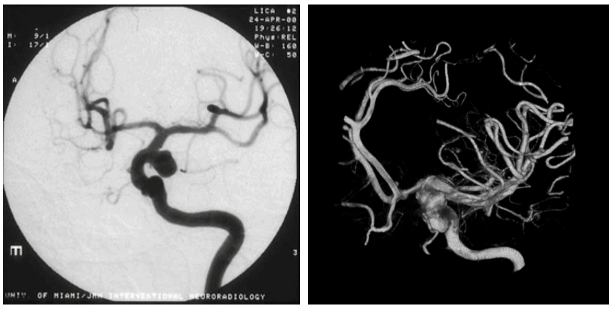


(a) 2D angiogram (b) 3D angiogram

Fig. 1. Two angiogram showing cerebral blood vessels. (a) 2D view (source: Neurosurg Focus, American Association of Neurological Surgeons) and (b) a 3D visualization.

cerebral interventional procedure to treat aneurisms is the endovascular embolisation, where the aneurism needs to be packed with coils. This process as well as other treatments require a good spatial comprehension of the vessel structures. As the images in Figure 1 show, the vessel structures segmented from angiography datasets are of a complex nature in terms of furcations and the number of vessels overlapping in depth. The spatial comprehension of these complex structure is impaired by mainly three reasons. First, the structure of the vessels and the accompanying abnormalities may vary. Thus the viewer can not resort to experiences and expectations in the perception process, which is done when perceiving things in everyday life where we have an *unconscious* understanding of the depth structure. Therefore it is especially hard for novices and medical students to spatially comprehend angiograms. The second reason making depth perception of angiography visualizations difficult is the loss of perspective distortion. Since physicians need to conduct measurements within an angiogram, e.g., measuring the length and thickness of a vessel, an orthographic projection has to be used in the visualization process to ensure that angles and lengths do not get distorted. However, orthographic projection does not allow to exploit the depth cue of perspective distortion, which we experience in everyday life when we perceive distant objects smaller. Another difficulty in depth perception of angiography images results in the loss of binocular disparity. In nature we perceive the depth information of close objects by exploiting the viewing parallax given by the distance between our eyes. Although in computer graphics this can be simulated by using stereoscopic techniques, either instrumenting the user with special glasses or using expensive autostereoscopic displays is necessary. Both techniques are not widely available and also not sufficient for everyday use as well as multiple observers. Thus binocular disparity is in most cases not present when viewing angiography images.

To improve depth perception, physicians often view angiograms under motion by rotating them interactively. Because of the rigidity of the structures, the rotation of a vessel complex may give clues about its structure. However, since an orthographic projection is used, no motion parallax is present. Thus the dynamic change of occlusion is the only depth cue arising when performing a rotation. It is obvious that motion cannot be used to enhance spatial comprehension of static images as they may appear in reports or print publications. Furthermore when a group of people watches a dataset it is not easy to talk about certain medical aspects while the object of interest is in motion, since it is not easy to find common reference points.

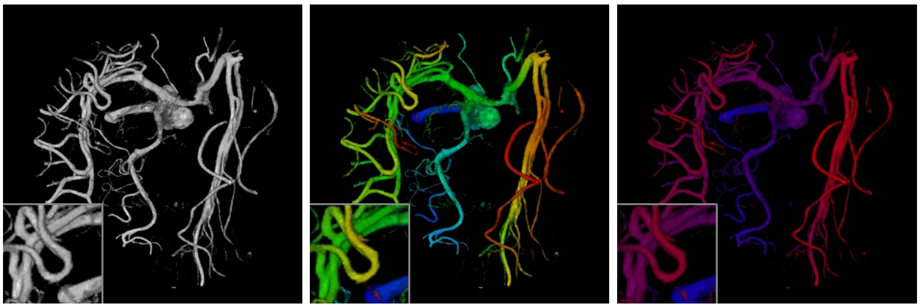
For a more effective as well as efficient analysis it is therefore necessary to develop visualization techniques which support the depth perception of potentially complex vessel structures without requiring stereoscopic display hardware. In this paper we propose and evaluate 3D visualization techniques developed with this goal in mind. Although the techniques have been developed for static images, they can be applied in real-time and are therefore also usable in interactive visualization applications. Furthermore they are of monoscopic nature, which allows to apply them in almost every standard desktop setting without instrumenting the user with special glasses. However, they may be combined with stereoscopic display technologies.

In the next section we are going to describe related work. We will focus on vessel visualization techniques with special consideration of angiography and some proposed models describing the process of depth perception. The visualization techniques we propose to enhance spatial comprehension of angiography images are described in Section 3, where we explain in detail how to color-code depth information, enhance occlusion, simulate perspective distortion and apply an effect similar to depth of field. All these presented techniques are evaluated and discussed in Section 4. Finally, the paper concludes in Section 5.

2 Related Work

The most common technique used for visualizing vessel structures is the maximum intensity projection (MIP). In contrast to this direct rendering, model-based approaches generate and visualize a model of the vessel system to support generation of high quality images. The initial work on this topic has been done by Gerig et al. in 1993 [1]. Hahn et al. describe an image processing pipeline to extract models of vascular structures in order to generate high quality visualizations [2]. In 2002 Kanitsar et al. have proposed a model-based visualization technique based on curved planar reformation [3]. Oeltze and Preim have introduced in 2005 the usage of convolution surfaces to further enhance visualization quality especially at vessel furcations [4]. While all other techniques focus on visualizing the vessel structures without contextual information, the *VesselGlyph* [5] provides also context information given by surrounding tissue.

Since we introduce monoscopic visualization techniques to enhance depth perception, a few references regarding this topic are given in this section. We do not discuss monoscopic depth cues in detail, instead we refer to [6,7] which give a good overview. A detailed comparison of the influence of depth cues on depth perception can be found in [8]. For estimating the interplay of depth cues,



(a) regular coloring (b) chromadepth (c) pseudo chromadepth

Fig. 2. Depth cues through color coding. The depth is not encoded in the color (a), chromadepth (b) pseudo chromadepth reduced to red and blue (c).

different models have been proposed. They all take into account the combination of different depth cues and postulate a way in which these depth cues contribute to the overall depth perception. The models incorporate for instance the weighted linear sum [9], a geometric sum [10], or the reliability of depth cues in the context of other cues and additional information [11].

3 Enhancing Depth Perception in Angiography

We have developed 3D visualization techniques to support depth perception in angiography datasets in order to make the comprehension of these datasets more effective and more efficient. All the presented visualization techniques are of monoscopic nature and can be applied to both still as well as dynamic images. Thus angiography datasets can be explored interactively.

Although shadows are commonly known to support depth perception of computer generated images [8], we have decided not to exploit shadow casting. With shadow casting a new *level of contrast* is introduced, given by the shadow borders. In order to remain simple images in terms of displayed borders and color variations, we are focussing on visualization techniques, which emphasize the present structure instead of introducing new structures, as for instance shadow borders.

The results of the evaluation we have conducted for the presented techniques are discussed in Subsection 4.2.

3.1 Pseudo Chromadepth

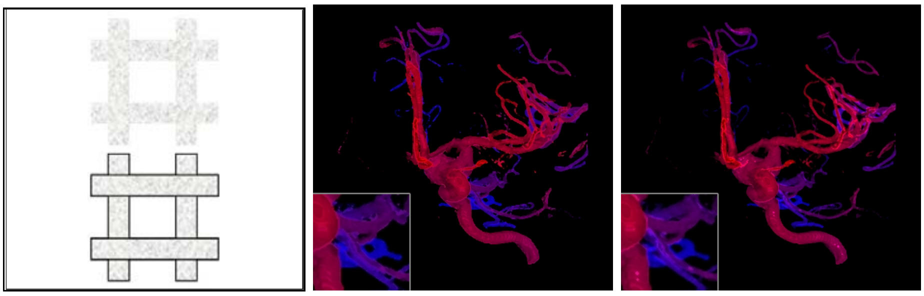
The chromadepth technique [12,13] supports depth perception based on the fact that the lens of the eye refracts colored light with different wavelengths at different angles. Although this effect can be supported by diffraction grating glasses watching appropriate images without instrumentation can also provide the depth effect. Thus a color-coding can be applied to an image, whereas the depth value at each pixel position is mapped to a corresponding color (see Figure 2 (b)). The advantage of this technology is that one can perceive depth in chromadepth pictures also without wearing eyeglasses. However, the selection of colors is limited, since the colors code the depth information of the picture. If the color of an object is changed, then its observed distance will also be changed. When visualizing vessel systems, except for the shading information the color channel usually contains no relevant information. Therefore we were able to apply a depth based color-coding to angiography.

An application of chromadepth color coding to an angiogram is shown in Figure 2 (b). It can be seen that there is a variety of hues present in the image. Since this variety distracts from the shading information, which is necessary to perceive the 3D structure, our goal was to reduce the number of hues used but still allowing a good depth perception. A reduction to a gradient of only two hues already allows a good visual separation of foreground and background elements (see Figure 2 (c)). As it can be seen in the image, we decided to use a gradient running from red to blue for increasing depth values due to two facts. First, the high wave length difference of red light (780nm) and blue light (450nm) results in a different focus point within the human eye. The shorter wavelength of the blue light results in a higher refraction and therefore the point of focus lies closer to the lens, therefore blue objects are perceived to be farther away. This is also the effect exploited in chromadepth images, whereas we concentrated on only two colors, namely those with the highest *contrast* in terms of depth perception. Another aspect important for choosing blue and red for color-coding depth information is the fact that the human eye has a higher color resolution for the colors red and green than for blue. Furthermore the time to respond to a signal varies according to the color used; dark colors lead to a relative high response time whereas light colors ensure quick response times.

When color coding the depth information we had to decide whether a color represents an absolute depth value given by the distance to the viewer or a relative depth value, measured by the depth expansion of the viewed dataset. Since usually only one angiogram is viewed at a time and the resulting colors in the image serve only the spatial comprehension within this particular view, the colors do not have to be comparable across different views or datasets. Therefore we have decided to normalize the depth values $frag_z$ to lie in the interval $[0.0, 1.0]$ and assign the color values by using $frag_{rgb} = (1.0 - frag_z, 0.0, frag_z)$, with the rgb components lying in $[0.0, 1.0]$. Since the normalization does not allow to draw conclusions about the quantitative depth expansion, we have added an appropriately labeled color gradient legend widget showing the color mapping for the occurring depth values.

3.2 Occlusion

As denoted by Ware in 2004 [14] occlusion is probably the strongest depth cue. This is due to the binary nature of occlusions which leaves not much space for misinterpretation. For instance, consider the WIMP paradigm, where multiple windows are displayed. Although the windows do not expand in depth, have



(a) occlusion illustration (b) overdrawn edges (c) blended edges

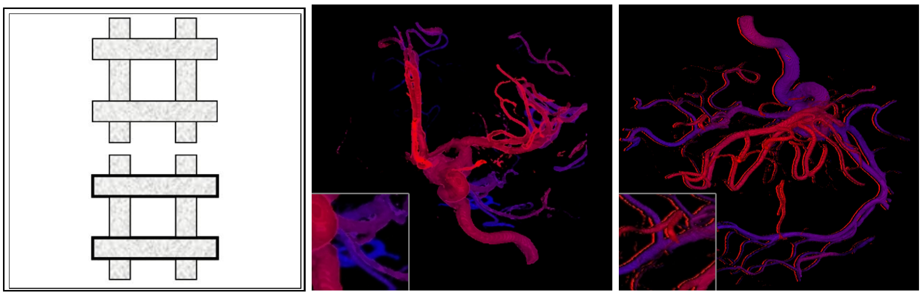
Fig. 3. Emphasizing the binary occlusion relation. Occlusions can be emphasized by enhancing the edges of similar colored objects (a), edges overlaid on the vessel structures (b) and edges blended with an opacity of 50% on the vessel structures (c).

the same distance to the viewer and no depth information is given except the occlusion, we get a sense of depth. This is also reflected in the vocabulary used when talking of the *topmost* window. Thus as Ware has stated, "occlusion is the strongest [depth cue], since when an object overlaps another, we receive it as *in front of* the other object, despite there are other depth cues present, stating the opposite".

Thus we have to ensure that occlusion supports the user when viewing angiograms. As it can be seen in Figure 1 (b) occlusion is already present when using regular volume rendering techniques. However, an occlusion is harder to perceive when the overlapping objects have a similar surface shading resulting in a low contrast. This effect, which can also be seen in Figure 1 (b), is illustrated in Figure 3 (a). Two overlapping polygons are shown, which have a similar surface texture, similar to vessels in an angiogram. In the lower picture the edges of the polygons are enhanced and thus the binary occlusion relation is more easy to perceive. To achieve this effect in vessel visualization, we apply an image-based edge enhancement technique [15] with the goal to emphasize the occlusions given by a vessel arrangement more clearly.

A drawback of the introduced edges is the fact, that the edges occlude parts of the shading. This is especially visible when looking at thin vessels. Since shading itself also serves as an important depth cue this effect has to be avoided. We do this by blending semi-transparent edges instead of rendering them with full opacity. The difference can be seen in Figure 3 (b) and (c), where in (b) an opaque edge is overlaid, while in (c) a semi-transparent edge with an opacity of 50% is blended. Notice that in both images the pseudo-chromadepth coloring introduced in the preceding subsection is applied to the edges.

When applying this technique it is important that the thickness of a vessel as displayed on the screen is not affected by the thickness of its edges. Otherwise it would not be possible to measure and compare the dimensions of vessels having a different distance to the viewer. Therefore we ensure that the edge is only visualized on top of those pixels belonging to the vessel anyway.



(a) perspective illustration (b) inverse linear mapping (c) edge shading

Fig. 4. Simulation of perspective distortion. Perspective distortion is depicted by varying edge thickness (a), the edge thickness varies inverse linearly to the distance (b) the edge is determined by considering the gradient with the south-west neighbor of each pixel (c).

3.3 Simulation of Perspective Projection

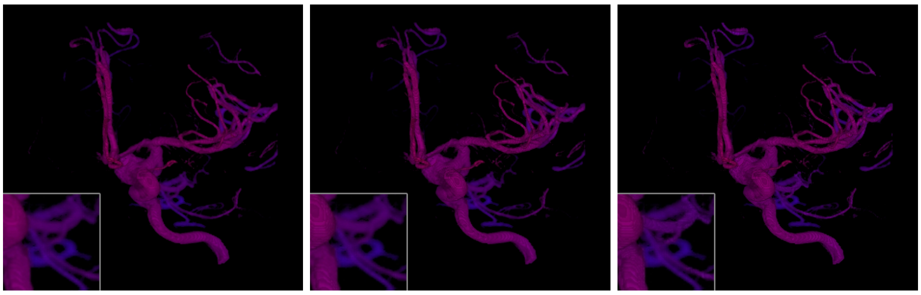
Since an orthographic projection is applied in angiography visualization vessel length and thickness is maintained regardless of the distance to the viewer. Thus the perspective distortion, which plays an important role in depth perception, is not present. However, in everyday live this distortion plays an important role, and we judge the distance of objects depending on their size.

To simulate perspective distortion in angiography imaging we use a varying thickness of the enhanced edges we have proposed in Subsection 3.2. Our technique ensures that edges become thinner with increasing distance to the viewer. The concept is illustrated in Figure 4 (a), where the edges of closer objects are thicker than those of objects being farther away. The technique has been applied to the angiograms shown in Figure 4 (b) and (c). While in (b) the thickness of the edge is inverse linearly proportional to the distance, in (c) a different edge detection algorithm. Therefore we take into account only depth gradients with the south-west neighboring fragment and achieve an appearance, which is similar to shading. The idea is to make the round structure of the vessel more clear, by applying these *fake highlights*.

Again, we ensure that the edges are only rendered on top of the vessels to preserve their thickness.

3.4 Depth of Field

When we look around in a real world environment we focus on certain objects located at a particular distance. All objects having the same distance and projection region on the fovea as the objects in focus are perceived sharply, while all other objects being closer or farther away from the viewer are perceived blurry. This rather gradual effect increases with distance and is denoted as *depth of field* or *depth of focus*. It can also be simulated in computer graphics. However, a



(a) distance threshold 10% (b) distance threshold 30% (c) distance threshold 60%

Fig. 5. Application of a modified depth of field effect with varying distance thresholds: 10% (a), 30% (b) and 60% (c)

problem occurs since as long as no head tracking device is used, it is not possible to measure which object is in focus of the viewer.

As shown in Figure 5 we have integrated a modified depth of field effect (further referred to as depth of field) into angiogram images in order to support depth perception. As expected and as it can be seen in the images, some parts of the displayed vessel structures become more blurry (for consequences of this effect refer to the discussion in Subsection 4.2). Since in our setup we aim to avoid the use of additional hardware, we had to apply a heuristic to find out on which objects the user is focussing on. When viewing angiogram images the view is usually changed by rotating the object. Through this rotation some of the vessel structures lying in the back get occluded by the parts lying in front. Thus more distant objects are harder to perceive, and therefore we assume that the viewer is focussing on the vessels being closer to the camera. For this reason, we have applied the depth of field effect only for those parts of a vessels whose distance from the viewer exceeds a certain threshold distance. The three images shown in Figure 5 show the depth of field effect applied with different threshold distances. This threshold distance is given as percentage of the depth interval of the vessel dataset. For instance, 40% means that when all vessels lie in the depth interval $[0.0, 1.0]$, depth of field is applied to all structures having a distance greater or equal to 0.4. In the images shown in Figure 5 we have chosen a threshold distance of 10% (a), 20% (b) and 30% (c).

Similar to the application of the depth based color encoding described above, we normalize all depth values of the vessel structure to lie in the interval of $[0.0, 1.0]$. Thus it is not possible to estimate the absolute distance from the viewer, but instead the relative distance of the vessels.

4 Evaluating the Proposed Visualizations

The 14 users participating in our user study had to perform simple tasks allowing us to estimate how effectively and efficiently depth can be perceived when viewing angiography images.

4.1 User Study

To perform the user study, we have implemented a simple evaluation application. The goal of the study was to measure the effectivity and efficiency of the depth perception when viewing 3D angiogram images. Since the influence of depth cues is task dependent [14,16], we had to choose a task similar to the diagnosis performed by physicians. However, there is no standardized viewing procedure, so we have decided to keep the task simple and hence minimize the influence on the perception of depth cues. Therefore the 14 participating users had to compare the depth of two vessels contained in an angiogram. Since we wanted to eliminate the influence of structure from motion, we made the task static, i.e., the users should estimate the depth based on a single image.

We compared the visualization techniques proposed in Section 3 to a standard 3D visualization as shown in Figure 1 (b) as well as a stereoscopic visualization generated using an autostereoscopic display. During the tests we have shown each user 10 series, each consisting of 5 images rendered using the same visualization technique. Since the perceptual interpretation of a single depth cue shown in isolation is affected by a prior presentation of a different depth cue in the same setting [17], we had to ensure that all the images a user was confronted with either show a different dataset or show the same dataset from a different perspective. The series were: standard rendering (see Figure 1 (b)), stereoscopic rendering, chromadepth (see Figure 2 (b)), pseudo chromadepth (see Figure 2 (c)), overlaid edges (see Figure 3 (b)), blended edges (see Figure 3 (c)), perspective edges (see Figure 4 (b)), edge shading (see Figure 4 (c)), depth of field (10%) and depth of field (10%) combined with pseudo chromadepth (see Figure 5 (a)). Because of their diverse functionality we decided not to evaluate a combination of depth of field with any of the edge based techniques.

In each image two random vessels have been highlighted by flashing square-shaped outlines of equal size. To not distract the user these outlines are displayed only the first 800 ms each image came up. In case the user wants to see these regions later on, she could make them appear as long as the spacebar is pressed. Before each image we have presented a message asking the user to select either the front most or the back most of the two highlighted vessels. This selection could be simply performed by clicking with the mouse inside or near the area of the corresponding square. We have measured the time needed for the selection for each image. Although each user was aware of the fact that we measure the time, we asked them to primarily focus on performing a correct selection than on being fast.

4.2 Results and Discussion

After each series the user had to answer a short questionnaire consisting of six questions displayed on the screen. The questions asked were regarding the depth impression, confidence to have performed a correct selection, approximation of selection time, reliability of the images, whether the images are considered usable for daily work and how appealing the images appear. Each question had to be answered on a six point Likert scale, were 1 is considered as a positive answer

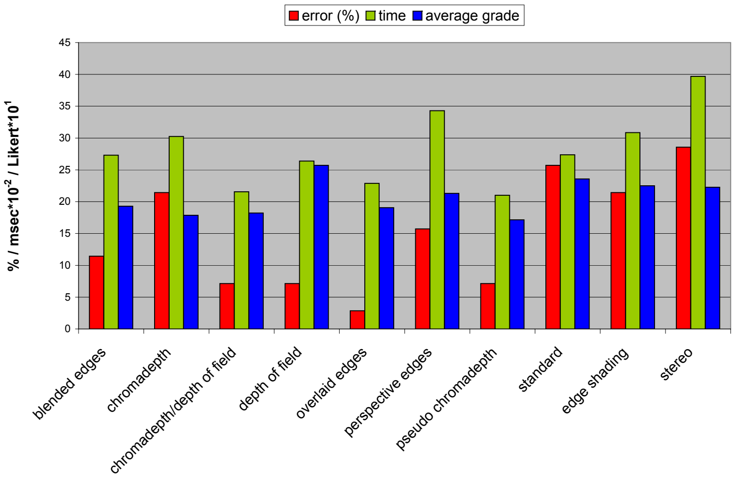


Fig. 6. Results of the user study: percentage of erroneous selections, used time and average rating based on questionnaire

and 6 is considered as a negative one. The average percentage of non correct selections, the mean time used to perform a selection as well as the average results of the questionnaire are shown in the diagram shown in Figure 6.

In an informal interview conducted immediately after the user study, the users were asked to denote their preferred visualization technique. Only 2 users said that they prefer to work with the autostereoscopic display, 4 preferred the chromadepth, 4 the pseudo chromadepth, 1 user the depth of field, 2 user the edge shading and 1 user the standard rendering technique. As shown in Figure 6, the standard rendering technique as well as the stereoscopic one did not lead to good results. While with the standard technique this is obvious since the depth information is not available, we expected better results for stereoscopically rendered images. We believe, the reason for the bad results is, that only 4 of the participating users had experience using autostereoscopic displays. Although we asked each participant to test the display before the study and we ensured that there is time available for finding the sweet-spot before the stereoscopic series, the users seemed to have problems perceiving the stereoscopic images.

Chromadepth uses more hues than pseudo chromadepth and should therefore allow to better measure differences in depth. However, it can be seen in Figure 6, that with pseudo chromadepth the users have achieved in average more correct and faster selections. It reduces the error rates about 18% in comparison to the average error rate given by the standard technique. A statistical analysis has revealed, that the hypothesis, that pseudo chromadepth reduces the error rate can be assumed as true with a level of significance of 5%. Furthermore pseudo chromadepth received a slightly better average grade in the questionnaire. This may be due to the fact which came up in the following interview, that 6 users were overwhelmed by the amount of hues present in a chromadepth image. However, as mentioned above we did not explain the color coding in advance;

maybe chromadepth would be more effective and efficient in case we would have explained the techniques before performing the study.

Depth of field also gave quite good results in terms of correctness. However, the response time has been increased, which we ascribe to the fact, that some users may had the impression that the picture is out of focus and hence did need some time to try to get it in focus. This is also reflected in the bad given average grade shown in Figure 6. Again this could be different when we would have informed the users about the technique in advance. Although the overlaid edge technique did lead to very few wrong selections, the edge techniques in general seem not to be very effective nor efficient. Especially the perspective edge technique might be distracting and lead to over 15% of selection errors and quite long selection times.

5 Conclusions

We have presented a set of monoscopic 3D visualization techniques serving as depth cues and thus supporting the depth perception of vessel structures shown in angiography images. After we have given a brief overview of depth perception related to angiography, we have proposed the application of interactive 3D visualization techniques to support exploring 3D angiography images. Namely, we applied color coding depth information, depicting occlusions by means of edge detection, simulating perspective by varying edge thickness as well as style and the application of depth of field.

Our evaluation has indicated, that angiography seems to benefit from color coding depth information. Especially the pseudo chromadepth technique combined with a depth of field effect is promising to improve spatial comprehension. In the future it would be necessary to validate our results by performing a more broad user study. In this study a closer look to the usage of the colors is necessary, e.g., to distinguish clearly between the physical effect caused by the different refraction of different wavelengths and the cognitive effect of color coding as well as how a semantic color coding used in certain domains influences the effect. To achieve a better image quality it would be interesting to combine the proposed techniques with model-based visualization of vessel trees.

Acknowledgements

For a color version of the figures go to viscg.uni-muenster.de/sg06. The authors thank Hagen Schiffbauer for providing valuable insights into how to perform a medical diagnosis based on angiogram datasets and Lucia Terrenghi for discussing ideas about the evaluation. This work was partly supported by grants from the Deutsche Forschungsgemeinschaft (DFG), SFB 656 MoBil Münster, Germany (project Z1).

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