Visualization and Evaluation of Intra-Bundle Diffusion Characteristics

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Abstract: Diffusion imaging is a unique MRI technique which reveals vital information about the constitution of neuronal pathways in vivo. Intra-bundle diffusion information is crucial for the analysis of white matter in the human brain. Previously introduced bundle visualizations aim at delineating intra-bundle diffusion characteristics by applying hull generation, diffusion analysis, color mapping, as well as illustrative rendering. In this work, we present a user study which focuses on evaluation of these approaches in terms of general understanding, spatial depth perception, and possible applications.

1   Introduction

Diffusion imaging is an MRI-based technique measuring molecular movement in tissue. It enables white matter examinations in vivo and is therefore of great interest in neuro-visualizations. High angular resolution diffusion imaging (HARDI) emerged to overcome the limitations of diffusion tensor imaging (DTI) in terms of multiple diffusion directions within one voxel. Tractography techniques, also called fiber tracking, provide the identification of neuronal pathways. The course, position, and integrity of fibers can be vital in neurosurgical examinations, to evaluate the extent of an intervention, as well as in fundamental neuroscience, to extract neuronal connections related to specific tasks. In most of the cases, tractography methods result in simple line representations. However, lines can be misleading since diffusion values are merely an approximation of the underlying diffusion present within one voxel. Therefore, diffusion visualization approaches using fiber encompassing hulls emerged [MME+09]. These hulls are conventionally single colored and do not provide any information about spatial placement or fiber integrity. Therefore, in our previous work [RDMM12a] we presented a method to visualize inner-bundle diffusion characteristics using a raycasting approach. Bundles are colored to delineate the underlying diffusion process. In addition, we integrated visual enhancements to facilitate bundle exploration. In the following, we will briefly explain the proposed inner-bundle visualization approaches, discuss results, and subsequently present a user study which was performed to evaluate the visualizations in terms of general understanding, spatial perception, and neuroscientific applications.

2 Related Work

Diffusion data visualizations can be categorized in either local or global approaches. Global methods include tractography techniques which reconstruct and visualize the course and position of neuronal pathways oftentimes along with anatomical data. Methods aiming to display local diffusion profiles concentrate on diffusion processes present in one voxel. Local methods reveal information about tract integrity and local fiber distribution. Benefits of both categories are combined within the presented approach. Therefore, we will present a short literature review of both in the following.

Tractography methods [BPP+00,LWT+03,DDKA09] use diffusion maxima, either resulting from DTI or HARDI, to reconstruct neuronal pathways. However, they conventionally do not visualize information about local diffusion profiles, such as diffusion classifiers. In order to visualize the underlying diffusion pattern directly, rather than extracting information for tract reconstruction, a geometrical representation, known as *glyphs*, emerged for DTI and HARDI [Kin04, PPvA+09]. However, glyph interpretation is difficult and exploration challenging, especially for clinicians who are not used to this representation mode.

Diffusion indices, such as the fractional anisortopy (FA) [BP96] for DTI or the generalized fractional anisotropy (GFA) [Tuc04] or the isotropic, single, multiple diffusion index (ISMI) [RDMM12b] for HARDI, feature information about the local degree of linearity. These indices provide vital information concerning fiber integrity or intra-voxel fiber distributions. However, an anatomically meaningful and intuitive visualization is challenging.

An approach for DTI-based fiber bundle characteristic quantification was proposed in [KHK+07]. The method first resamples a fiber bundle and computes an average principal fiber. Subsequently, orthogonal planes are used to compute FA values on the cross-section of the bundle. Similar to the approach presented in this paper, integrity information was visualized on bundle surfaces in [GWH+11]. The authors used slicing planes to extract diffusion information and interpolated index values of two neighboring slices to obtain a color value for a specific vertex.

3 Intra-Bundle Visualization Approaches

In the following, precomputations as well as visualization methods proposed in our previous work [RDMM12a] will be explained in brief.

3.1 Precomputations

The intra-bundle diffusion visualization methods require the following diffusion precomputation steps:

- *Q-ball imaging*, to utilize HARDI diffusion datasets [DAFD07],

- *tractography*, in order to reconstruct neuronal pathways [RSM11],

- *voxel classification*, to describe the underlying diffusion [RDMM12b],

- *hull generation*, defines an encompassing bundle geometry, and

- *centerline extraction*, using a skeletonization approach.

Results of the HARDI-based tractography approach are shown in Figure 1, visualized as GPU-based view-dependent triangle strips as proposed in [RDM12].
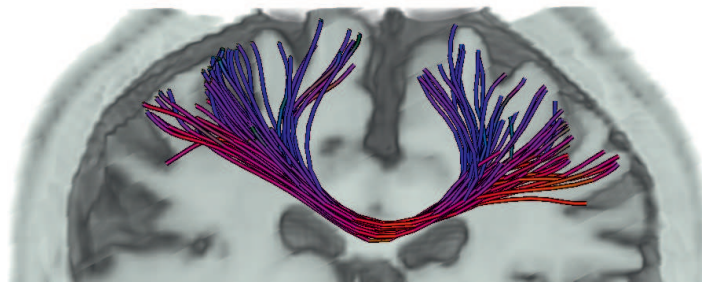
Figure 1: Streamline visualization of callosal fiber pathways used to generate fiber hulls.

These precomputations contribute to the final intra-bundle visualizations, which are presented in the following. For detailed information about the algorithms, we refer to the original publication. Visualization results of the single methods are shown in Figure 3 and Figure 4.

3.2 Bundle Raycasting

The intra-bundle raycasting approach uses the hull geometry as input for a GPU shader pipeline. The centerline of the fiber tract is necessary for ray computation and the diffusion characteristic volume for color mapping. Both are integrated via textures in the shader pipeline. The vertex shader is in charge of computing texture coordinates for characteristic evaluation, as well as the nearest point of the centerline. Further, a ray is traced from the current hull's vertex to the obtained centerline point. In the following, this ray is used for diffusion characteristic evaluation. In this case ISMI is utilized as a diffusion index, however, it can be replaced by others such as FA or GFA. We developed the following visualization strategies for intra-bundle raycasting which are motivated by volume rendering approaches:

Diffusion Averaging. *Diffusion Averaging* computes the mean diffusion characteristic value out of samples along the ray from the vertex to the nearest centerline point.

Min/Max Diffusion. The *Min/Max Diffusion* mode computes the minimum and maximum diffusion index value along the ray for color mapping. Therefore, a single characteristic value is displayed.

Diffusion Slider. Using the *Diffusion Slider*, an interactive examination of diffusion characteristics along the ray from the vertex to the centerline is provided. For this visualization the ray is sampled at discrete points and diffusion characteristics from the hull to the centerline can be displayed.

Diffusion Variance. In order to differentiate homogeneous from inhomogeneous regions we developed the *Diffusion Variance* mode. Variance of diffusion characteristics along the traced ray are computed and highlighted through color mapping.

Color Maps and Visual Enhancements. Two different color maps were used to emphasize the different meanings of both indices. The first color map describes local diffusion and encodes values of the diffusion classifier ISMI. It ranges from red to green and describes the present intra-bundle fiber configuration. Red indicates single and yellow multiple fiber configurations. Green is used to describe isotropic diffusion. The second color map is used to encode the variance of diffusion values: regions with high variance are colored in cyan and regions with low variance in purple.

The following visual enhancements were integrated in order to facilitate a three-dimensional understanding of the bundle shape: silhouette rendering, Phong shading and ambient occlusion. For silhouette rendering we applied a simple deferred shading approach introduced by Saito et al. [ST90]. Variances of neighboring normals are compared in order to define edges. To introduce shadow and thereby provide a hint for spatial depth, a Screen-Space Ambient Occlusion (SSAO) approach was implemented. This approach was first introduced by Mittring [Mit07] and samples the depth buffer in the neighborhood of each fragment. Generally speaking, the number of fragments closer to the viewport than the current one is used to darken the current fragment's color. However, combining color maps with enhanced rendering techniques to facilitate depth perception alters color appearance and can lead to false interpretations. Therefore, an evaluation of the introduced rendering techniques was performed in the course of a user study with clinical experts and will be discussed in Section 4. Figure 2 illustrates the implemented depth enhancements for the bundle used within this paper.

3.3 Centerline Slicing

Using the aforementioned precomputations, which are the geometric hull, the centerline, and the diffusion characteristic volume, a second visualization was implemented, the *Centerline Slicing*. This approach uses a plane orthogonal to the tangent of a user-specified centerline point. This plane is utilized to visualize the color-coded index by texture map-
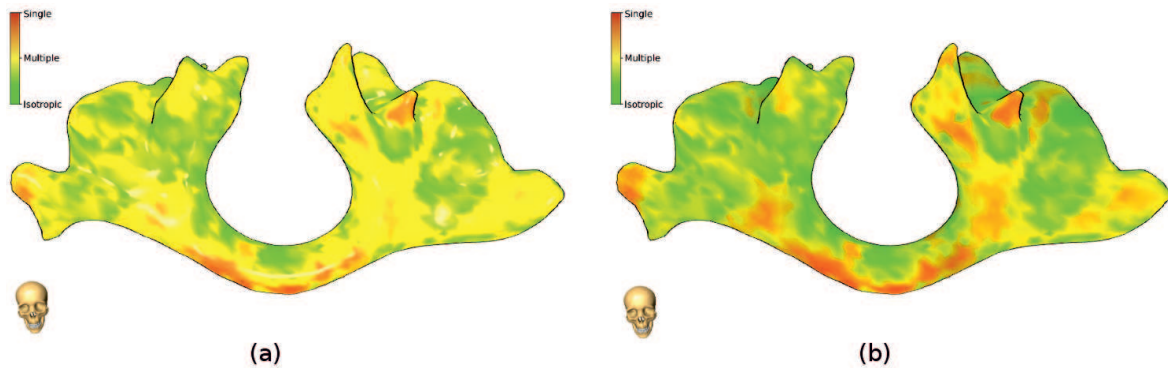
Figure 2: Visualizations for spatial depth enhancements. Both images feature the *Min Diffusion* mode and include silhouette rendering. Phong illumination (2a) and ambient occlusion (2b).

ping. Figure 5 displays the coordinate definition procedure for centerline slicing: the user selects a point through a mouse click on a rendering of the centerline.

4 User Study

Expert evaluation of the previously proposed methods was performed at the Neuroscience Unit, Institute of Biomedicine/Physiology, University of Helsinki and at the BioMag Laboratory at the Helsinki University Central Hospital. Seven students, researchers and medical doctors in the field of neuroscience participated and rated the approaches with respect to usability in neuroscience and visual understanding. The evaluation was designed to answer the following major questions:

- Whether the approaches provide a better understanding of the data,

- if the introduced perception enhancements facilitate depth impression and how they affect the understanding of the visualizations, as well as

- in which neuroscientific and neurosurgical questions the approaches can be beneficial.

Therefore, the approaches were presented and evaluated in two stages. At first, previously introduced intra-bundle visualizations were introduced to the audience in form of a presentation. The second part was performed using two different questionnaires. At first, experts discussed and rated the presented approaches in terms of understanding and usefulness and suggested a field of application. Secondly, experts evaluated the bundle shape perception: Perception enhancements are accompanied by changes in color and therefore potentially affect bundle diffusion interpretation. Thus, a trade-off between depth perception and adequate color map illustration exists and the decision for the best visualization is challenging. Therefore, illustrations featuring single and combined Phong illumination,
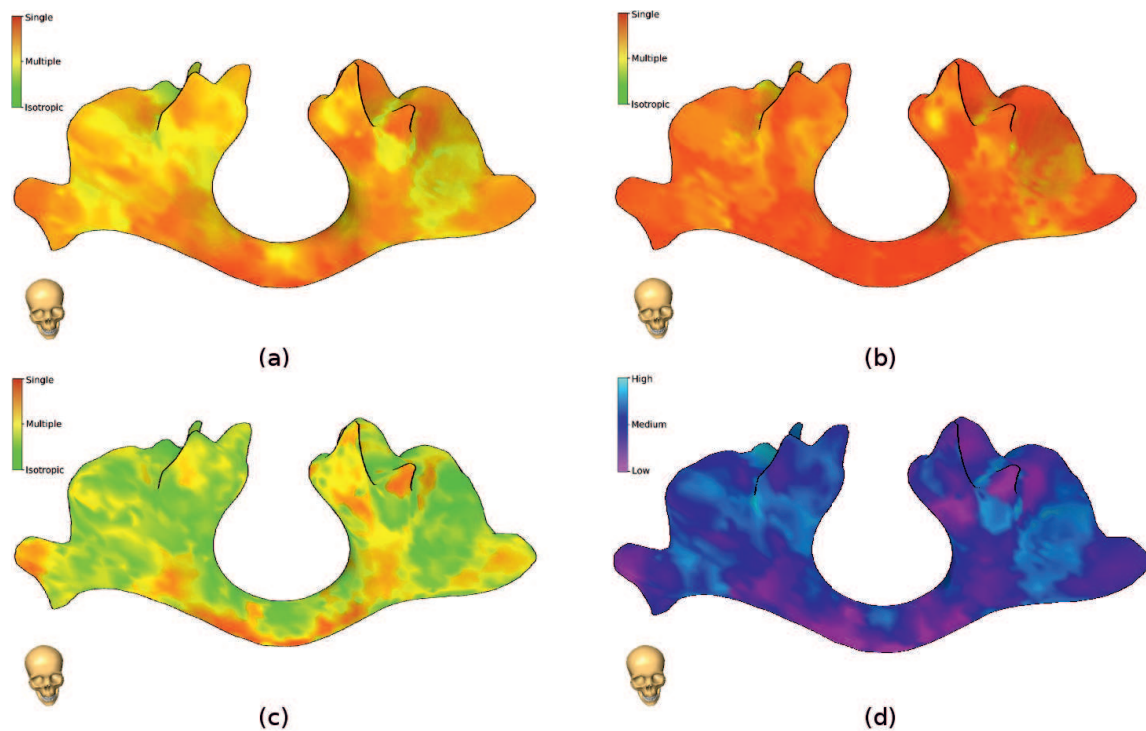
Figure 3: Intra-bundle raycasting results: *Diffusion Averaging* (3a) and *Max Diffusion* (3b) show multiple fiber distributions in the *centrum semiovale* in yellow. In the *Min Diffusion* (3c) visualization mode, red reveals regions with highest integrity. The *Diffusion Variance* (3d) color encoding highlights high variance in cyan and low variance in purple.

silhouettes, and ambient occlusion were presented. Experts rated the clarity and improvements of the visualizations with consideration to spatial depth perception and bundle color interpretation. Figure 6 presents individual stages of the user study.

4.1 Visualization Methods

The *Diffusion Averaging* approach was one of the favorite visualizations amongst experts. They stated that a good first impression about the underlying diffusion is provided and that it is a straightforward visualization. The *Min/Max Diffusion* modes are helpful in terms of identifying regions of multiple fiber populations and linear diffusion profiles. In the presented diffusion characteristic scheme an applied minimum diffusion raycasting mode reveals areas with highest single fiber population. Reconsidering Figure 3 and the *Minimum Diffusion* visualization, regions appearing red (the center of the *corpus callosum*) include no isotropic diffusion since the isotropic diffusion has a lower index value than the single fiber distribution. Hence, red areas in this visualization mode can be considered as the most directional fiber pathways. On the other hand, regarding the *Max Diffusion* visualization, yellow marked regions comprise no single fiber distributions since the maximum value is visualized and single fiber distributions comprise a higher index value than multiple. The evaluation of diffusion values at the centerline of a bundle using the *Diffusion*
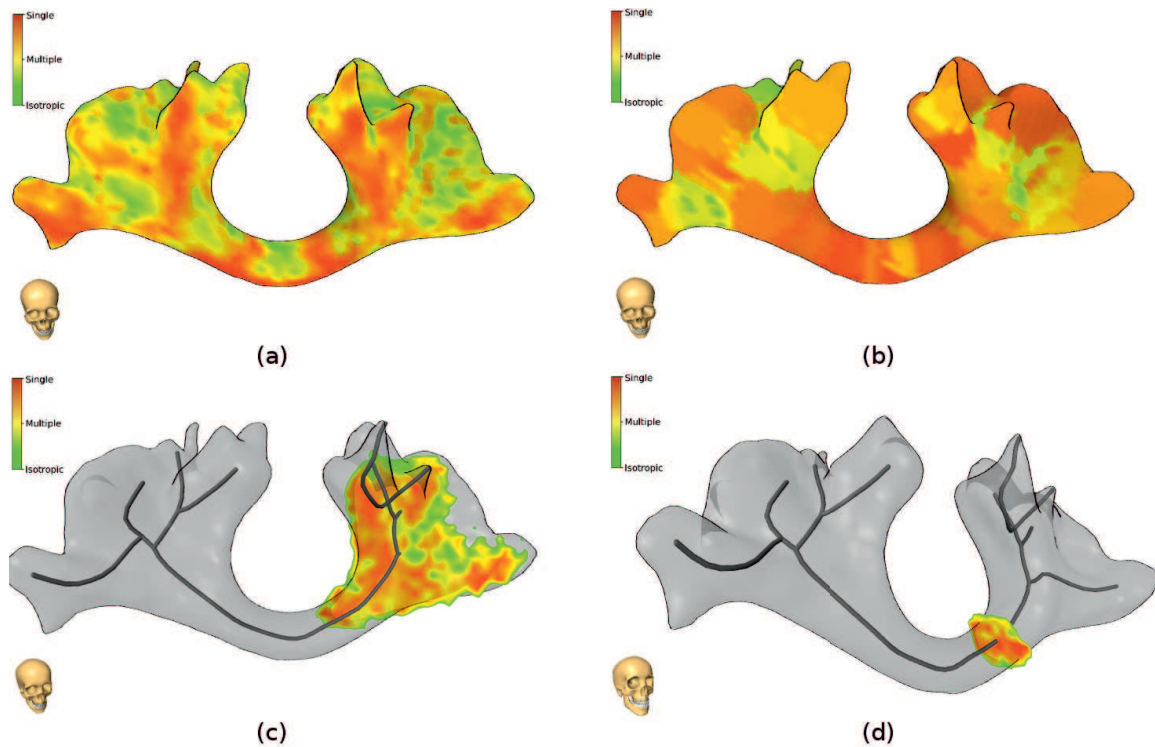
Figure 4: The *Diffusion Slider* displays diffusion values on the hull (4a) and the centerline (4b). Green indicates parts of the hull leaking into gray matter (isotropic diffusion). The center of the *corpus callosum* comprises high single fiber configuration. *Centerline Slicing* within regions of complex diffusion profiles; plane corresponds to the defined point in Figure 5 is oriented with the view-vector (4c) and in the center of the *corpus callosum*, plane is orthogonal to the centerline's tangent (4d).

Slider mode is of special interest since the centerline can be considered as the skeleton, representing a whole tract. Therefore, diffusion values of the centerline are especially helpful in tract-based examinations. Visualizations of diffusion characteristics on the hull can be considered as an uncertainty visualization, since green parts indicate isotropic diffusion, and hence, these parts of the reconstructed bundle do not belong to a neuronal pathway, the bundle leaks into gray matter. The hull representation in Figure 4 additionally exhibits an interesting fact: The hull grows into the cingulum bundles which are two white matter tracts running above the corpus callosum and here indicated by the two red parts on top of the center. Results of the *Diffusion Variance* visualization correspond with the findings of the *Min/Max Diffusion* mode. Regarding the center of the *corpus callosum*, we can identify similar values in both of the *Min/Max Diffusion* visualizations, as well as in the right upper part. These regions appear in purple and indicate low variance. Considering the fanning regions of the *corpus callosum*, we can identify deviating values in the min/max visualizations in terms of multiple and isotropic diffusion; these regions are highlighted in blue and cyan in the variance diffusion mode. Regions where the bundle leaks into gray matter comprise the largest variance values within the voxel classification values and are marked in cyan. Within the *Centerline Slicing* mode, a more detailed examination of the
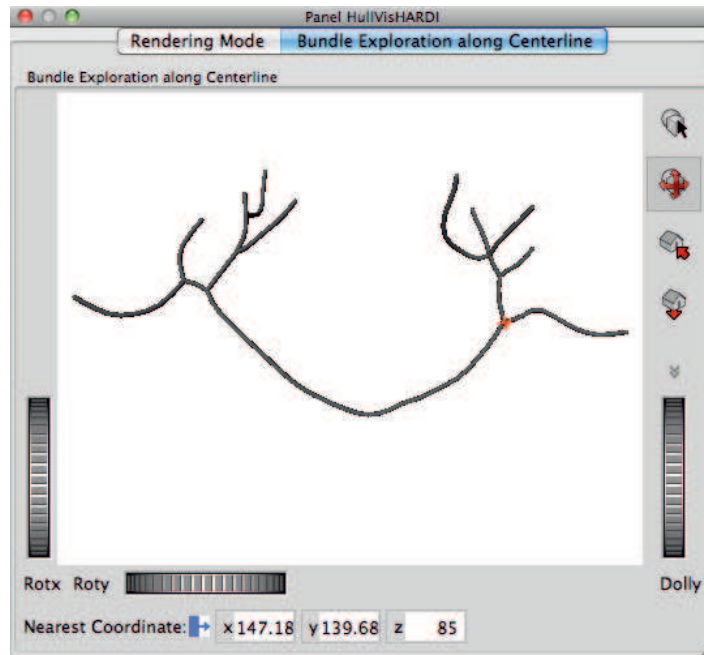
Figure 5: User interaction to define the point on the centerline for plane generation.

diffusion profiles is provided. This can be beneficial for e.g. regions with high variance, for example, and therefore considered as a subsequent step. Additionally, this visualization can be integrated in the operation microscope during surgery by means of an overlay to indicate pre-operatively computed diffusion characteristics directly on the brain. The findings within the visualizations correspond with the medical knowledge of the *corpus callosum*: The center of the *corpus callosum* is the area with the highest integrity and the highest directionality as well. However, the region of the *centrum semiovale* comprises more difficult fiber distribution profiles, such as crossings of the *corticospinal tract* and the *corpus callosum*. These configurations are revealed with our visualizations.

4.2   Visual Enhancements

When choosing between single Phong illumination, ambient occlusion, silhouettes, and visualization with no depth enhancement, ambient occlusion was rated to feature the best depth impression. Also, when adding silhouettes to the visualizations, all participants agreed that the combination of ambient occlusion and silhouettes as displayed in Figure 2 is the best depth encoding visualization. Single silhouette enhancement was placed second. The participants recognized the changes in terms of color appearance, caused by ambient occlusion, and Phong illumination, but rated the influence for Phong as more violating color interpretation than ambient occlusion. In addition, they judged depth encoding as a crucial feature for bundle-visualization. However, weather spatial depth perception or accurate color map visualization is more important to experts could not be significantly determined. Therefore, we decided to allow the user to enable or disable single visual-

1. **Presentation of the developed intra-bundle visualizations**
2. **Questionnaire I: understanding and potential applications**
- personal data (position and field of research)
- identification of the most significant approach
- understanding and usefulness
- potiential clinical applications
3. **Informal discussion of potential findings revealed by the visualizations**
4. **Questionnaire II: rating of individual visual enhancements**
- understanding
- depth impression
- differences in color interpretation

Figure 6: Stages of the user study.

ization enhancements manually. In general, Phong illumination was rated to be very confusing and led to severe changes in terms of color appearance and resulting misinterpretations considering tract integrity and diffusion distributions were observed. Summarizing, the most favorite visualization is ambient occlusion in combination with silhouettes, but should be switched off for color interpretation.

4.3 Application to Neuroscience

Experts think that the provided visualizations are of great interest in their field of research and can be beneficial to answer specific neuroscientific questions. The *Diffusion Averaging*, *Min/Max Diffusion*, and the *Diffusion Variance* modes are of specific interest. The *Diffusion Compositing* mode provides a good first overview, the *Min/Max Diffusion* and the *Diffusion Variance* visualizations highlight regions of interest, such as areas with multiple maxima or potential abnormalities which influence the local diffusivity. In terms of applications to neuroscience, they mentioned amongst others: Neurosurgical planning, such as lesion detection and analysis, as well as disorder monitoring, for example in stroke patients. Furthermore, an integration of the approach into a transcranial magnetic stimulation (TMS) system is feasible: Visualizing diffusion characteristics of neuronal pathways, originating from certain regions activated by TMS, can provide information about brain connectivity and integrity, which is of major interest in fundamental neuroscience. In addition, using this information, further TMS regions can be defined and evaluated for activation or blocking. Further, brain development in children seems to be an interesting application.

5 Conclusion and Future Work

In this paper we evaluated two visualization techniques for intra-bundle diffusion characteristics using HARDI-based fiber reconstruction and diffusion profiles. Today, it is possible to describe intra-voxel diffusion patterns using HARDI classifiers, but an effective, user-friendly, and problem-specific visualization had been missing. However, an intuitive visual exploration of diffusion characteristics in combination with tract morphology is of great interest in fundamental neuroscience and in many clinical applications. With our intra-bundle visualization approach we are taking a step forward towards a combination of global tract morphology and diffusion characteristics for HARDI. As a result of a user study, experts deemed the approaches useful and providing a better understanding as well as interpretation of diffusion data.

Considering HARDI fiber tracking results, hull representations encompassing different neuronal pathways may overlap with one another. Therefore, a visualization which is able to manage overlapping regions is needed. Potential approaches include the use of emphasis or focus and context rendering techniques. In this paper we used the previously proposed ISMI index for visualization, but others, such as the generalized fractional anisotropy (GFA), are possible as well. From the medical point of view it is interesting to evaluate the application of the presented visualizations in a neurosurgical setup. Additionally, a problem-specific visualization is feasible using our approach as well as combinations of characteristic evaluations. If, for example, the aim is to detect a lesion, the *Diffusion Variance* mode, which provides a focus on fiber integrity, could be beneficial.

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