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Visibility-Weighted Saliency for Volume Visualization

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Abstract

Volume visualization has been widely used to depict complicated 3D structures in volume data sets. However, obtaining clear visualization of the features of interest in a volume is still a major challenge. The clarity of features depends on the transfer function, the viewpoint and the spatial distribution of features in the volume data set. In this paper, we propose visibility-weighted saliency as a measure of visual saliency of features in volume rendered images, in order to assist users in choosing suitable viewpoints and designing effective transfer functions to visualize the features of interest. Visibility-weighted saliency is based on a computational measure of perceptual importance of voxels and the visibility of features in volume rendered images. The effectiveness of this scheme is demonstrated by test results on two volume data sets.

Categories and Subject Descriptors (according to ACM CCS): I.6.9 [Simulation, Modeling, and Visualization]: Visualization—Volume visualization

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1. Introduction

Volume visualization is an active branch of scientific visualization. It is a method of extracting meaningful information from volumetric data sets, which usually contain complex structures of various material. First introduced by Levoy [Lev88] for visualization of volume data, volume visualization has been widely used in various sciences to create insightful visualizations from both simulated and measured data.

A crucial step in volume visualization is transfer function specification. Transfer functions assign visual properties, including color and opacity, to the volume data being visualized. Hence transfer functions determine which structures will be visible and how they will be rendered. An appropriate transfer function can quickly reveal large amounts of information of the data set to the viewer. However, obtaining an effective transfer function is a non-trivial task, which involves a significant amount of tweaking of color and opacity. A cause of this problem is the lack of an objective measure to quantify the quality of transfer functions [CM11].

Although user studies are useful in evaluating some fundamental characteristics of visualization techniques, it is not possible to conduct a user study for each individual visualization every time it is created. Several computational measures of visual saliency that model human attention have been developed [IKN98] [HKP06]. Kim and Varshney [KV06] introduced the saliency field, which measures visual saliency of voxels using the center-surround operator based on the difference of Gaussian-weighted averages at a fine and a coarse scale. However, salient voxels may be occluded by other voxels close to the viewer in certain viewpoints and thus these salient voxels become invisible in the volume rendered image. In order to measure the visual saliency of features in volume rendered images, it is necessary to consider both the saliency and the visibility of the voxels which form the feature.

In this paper, we propose visibility-weighted saliency as an improved measure of the visual saliency of features in volume rendered images. Visibility-weighted saliency is a combination of feature visibility [WZC*11] and the saliency field [KV06]. Feature visibility measures the contribution of each feature to the volume rendered image and saliency field measures the visual saliency of each voxel in its local neighborhood. The visibility-weighted saliency are presented in two different ways, i.e. visibility-weighted saliency fields and feature saliency histograms. Visibility-weighted saliency fields display the spatial distribution of visual saliency of features and feature saliency histograms provide quantitative information about the perceptual impor-

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tance of the features. With visibility-weighted saliency, the saliency of features rendered in different viewpoints with different transfer functions can be measured in a quantitative and fully automated way. Thus, this technique can be used to guide users in choosing appropriate viewpoints and designing effective transfer functions for the features of interest in volume visualization. This technique is also useful for understanding how much different parts of the volume contribute to the final image and how different tissues occlude each other and interfere with each other's visibility.

2. Related Work

Transfer functions have played a crucial role in volume visualization and the design of transfer functions to generate informative visualizations has been a significant challenge addressed by a number of researchers [PLB*01]. Various strategies have been proposed to simplify transfer function specification [HKRs*06]. In volume data, boundaries are regions between areas of relatively homogeneous material. It is difficult to detect boundaries because different materials often consist of overlapping intensity intervals. To address this problem, multidimensional transfer functions used derived attributes such as gradient magnitudes and second derivatives along with scalar values, in order to detect transitions between relatively homogeneous areas [KD98] [KKH02] [Kin02]. In this case, the transfer functions are extended to multidimensional feature spaces. As a result, the interaction of transfer functions becomes more complex and unintuitive as the dimensionality becomes higher. Even in the case of two-dimensional transfer functions, a considerable amount of user interaction is required in order to come up with meaningful results [AD10].

Several computational models of visual saliency for modeling human attention have been developed. Itti et al. [IKN98] developed a computational model of visual attention based on the center-surround operators in an image. This center-surround mechanism has the intuitive appeal of being able to identify regions that are different from their surrounding context. Lee et al. [LVJ05] proposed saliency for meshes based on a multi-scale center-surround mechanism that operates on local curvature. Kim and Varshney [KV06] presented the use of a center-surround operator using the Laplacian of Gaussian-weighted averages of appearance attributes to enhance selected regions of a volume and validated their work using an eye-tracking user study. Shen et al. [SWL15] extended this technique to spatiotemporal volume saliency to detect both spatial and temporal changes.

Visibility measures the impact of individual voxels on the image generated by a volumetric object and visibility distribution can be utilized as a measure on the quality of transfer functions as users explore the transfer function space. Visibility has been studied to measure the quality of a given viewpoint [BS05] [VKG04] and to enhance the rendering process with cutaway views. Correa and Ma [CM11] introduced visibility histogram, which describes the distribution of visibility in a volume rendered image. Ruiz et al. [RBB*11] proposed an automatic method to generate a transfer function by minimizing the Kullback-Leibler divergence between the observed visibility distribution and a target distribution provided by the user. Want et al. [WZC*11] extended the idea of visibility histogram to feature visibility and introduced an interaction scheme where the opacity of each feature was generated automatically based on user-defined visibility values. Visibility distribution is also used in automating color mapping [CTN*13] and 2D transfer functions [QYH15].

3. Method

For 2D images, intensity and color are the most important attributes. In volume visualization, the intensity and color in the final images result from the blending of alpha and color determined by user-specified transfer functions in a specific viewpoint. The saliency field is a view-independent scalar field that contains the visual saliency of each voxel in the volume data. The visual saliency of voxels represents the perceptual importance in 3D space, however it does not reflect how visible the voxels are in the final 2D images.

In order to take into account both the visual saliency of voxels in 3D space and the contribution of the voxels to final 2D images, we propose a visibility-based saliency metric, which attempts to measure the impact of individual voxels as well as user-specified features on volume rendered images. This technique aims to assist users in gaining insight into the internal structure of the data set and understanding the contribution of different features to the final image.

The visibility-based saliency field is based on a visibility field and a saliency field. The visibility field contains the opacity contribution of each voxel to the final 2D image and the saliency field represents the visual saliency of each voxel in the 3D volume data.

In this section, we describe visibility fields, saliency fields, visibility-weighted saliency fields and weighted feature saliency. In order to better illustrate the effects of these techniques, we present the results of applying these techniques to an synthetic data set from two different viewpoints in our discussion.

3.1. Visibility Fields

Direct volume rendering (e.g. ray-casting) is a technique that renders a 2D projection of the 3D volume data set. The rendering of a volume, which essentially is a block of 3D data, involves alpha blending and color composition of voxels. The resulting 2D image is acquired by blending the color and opacity of voxels along the view direction. The transfer function determines the color and opacity of voxels based on their data attributes such as intensity. However, the contribution of a voxel to the rendered image is determined by both

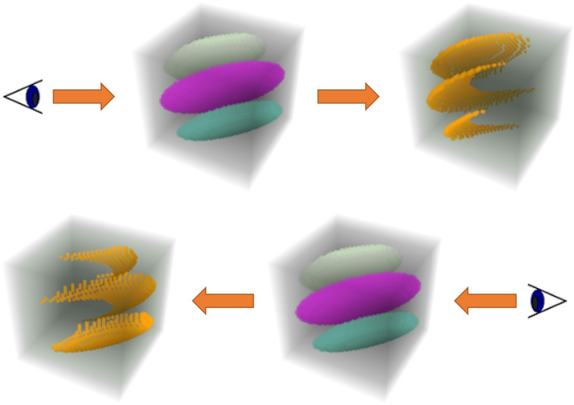

Figure 1: *A synthetic volume data consists of three solid disk-like objects. The images in the first row shows a final image and the corresponding visibility field from a viewpoint on the left. The images in the second row shows the the final image and visibility field from a viewpoint on the right. The visibility fields display what parts of the volume contribute most to the images and how tissues in the front occlude those in the back.*

the opacity of this voxel and the opacity of those voxels in front of the current voxel in the view direction. This mechanism is described in the front-to-back compositing equations [Ems08].

$$C_i = (1 - A_{i-1})c_i + C_{i-1} \tag{1}$$

$$A_i = (1 - A_{i-1})a_i + A_{i-1} \tag{2}$$

where a_i and c_i are opacity and color of voxel i, and A_i and C_i are the accumulated opacity and color at voxel i.

Therefore the visibility of voxel i can be calculated as

$$v_i = A_i - A_{i-1} = (1 - A_{i-1})a_i \tag{3}$$

and the visibility field is simply the visibility of all the voxels in the volume V

$$V = \{v_i \mid i \in V\} \tag{4}$$

The visibility field is dependent on both the viewpoint and the transfer function, therefore it can be used to analyze the structure of the volume data. The visibility field is particularly useful for understanding what parts of the data set are being rendered and how different tissues occlude each other (Figure 1).

In terms of implementation, the computation of visibility fields can be performed in real-time on a GPU. Correa and Ma [CM11] employed a scattering approach for GPU-assisted computation of the visibility histogram, which scatters the pixel points to the right bin in the histogram. Wang et al. [WZC*11] used the multiple rendering targets (MRT) extension of OpenGL 2.0 and above to achieve the computation of visibility for up to 32 features. Instead of grouping visibility values into intensity bins to acquire visibility distribution over intensity ranges (histograms), we are interested in the actual spatial visibility distribution, i.e. visibility field. We perform slice-based rendering on a GPU by rendering a series of quads which are parallel to the viewing plane, one for each slice. The fragments which do not belong to the volume are discarded. Then the visibility values are computed by subtracting the accumulated opacity of the previous slice from that of the current slice. After collecting the visibility values of all voxels, the visibility field can be constructed.

3.2. Saliency Fields

Because viewers pay greater visual attention to regions that they find salient [Pal99], many models of visual attention and saliency have been evaluated by their ability to predict eye movements. The saliency for a volume can be computed either by using eye-tracking data or through computational models of human perception. Once the saliency for a volume is acquired, it can be used to better inform the visualization process.

We use a center-surround operator that is similar to the work by Shen et al. [SWL15] to compute the saliency field. Let the neighborhood $N(i,\sigma)$ for a voxel i be the set of voxels within a distance σ. Thus, $N(i,\sigma) = \{j \mid \|j - i\| < \sigma\}$, where j is a voxel. Let $G(O,i,\sigma)$ denote the Gaussian weighted average, then we have

$$G(O,i,\sigma) = \sum_{j \in N(i,\sigma)} O(j) g(i,j,\sigma) \tag{5}$$

where

$$g(i,j,\sigma) = \frac{exp[-\|j-i\|^2/(2\sigma)^2]}{\sum_{k \in N(i,\sigma)} exp[-\|k-i\|]^2/(2\sigma)^2} \tag{6}$$

and O is a field of appearance attributes of every voxel in the volume and $O(j)$ is the appearance attribute of voxel j.

Then the saliency field is defined as the absolute difference of Gaussian-weighted averages

$$L(O,i,\sigma) = |w_1 G(O,i,\sigma) - w_2 G(O,i,2\sigma)| \tag{7}$$

where w_1 and w_2 indicate the weights of the Gaussian-weighted averages at a fine scale and a coarse scale respectively.

Visual properties such as opacity and color values (e.g. brightness, saturation, hue) can be used as appearance attributes in the computation of a saliency field. Figure 2 displays the saliency fields computed from brightness and saturation of voxels respectively. Although opacity is an important visual property, the visibility field described in the previous section is derived from alpha blending, which has taken the opacity of voxels into account. Therefore, we compute the saliency fields using brightness and saturation instead of opacity. Brightness and saturation are also the appearance

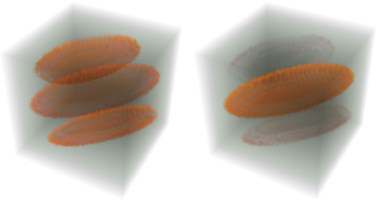

Figure 2: *The saliency fields computed from brightness (left) and saturation of voxels (right) respectively.*

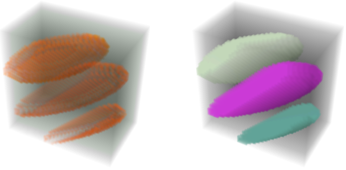

Figure 3: *The saliency fields emphasize the center and de-emphasize the surroundings of voxels. As in the clipped views of the saliency field (left) and the volume data set (right), the three solid disks are represented as hollow shapes in the saliency field.*

attributes Kim and Varshney [KV06] used in their saliency-based enhancement operator. The saliency field is acquired by applying the center-surround operator to appearance attributes of voxels. The effect of the center-surround operator is to emphasize the center and de-emphasize the surroundings of voxels. This is shown in the exploded view of the saliency field (computed from brightness) and the volume data in Figure 3.

In our implementation, we use perceptually uniform color spaces, e.g. CIELab and CIELCh. In CIELCh, instead of Cartesian coordinates a*, b*, the cylindrical coordinates C* (chroma, relative saturation) and h (hue angle in the CIELab color wheel) are specified, and the brightness L* remains the same. The advantage of using perceptually uniform color spaces is that the relative perceptual differences between two colors can be approximated by the Euclidean distance between the two colors in a three-dimensional space consisting of the three color components [Fai13].

3.3. Visibility-Weighted Saliency Fields of Features

The visibility field indicates the contribution of voxels, which is how much each voxel contributes to the final image, and the saliency field indicates the conspicuity of voxels, which is how much each voxel stands out from its surroundings. The conspicuity in a 3D volume is similar to that in an 2D image and can be measured by the difference of visible properties between each location (voxel) and its surroundings [DWMB11]. It would be desirable to have an indicator that represents both the contribution and conspicuity of the voxels. Therefore we propose a visibility-weighted saliency field, by weighting the saliency of voxels by their visibility, given the volume is rendered with a specific transfer function from a specific viewpoint. The visibility-weighted saliency for voxel i is

$$s_i(O,i,\sigma) = v_i L(O,i,\sigma) \tag{8}$$

Hence we define S as the visibility-weighted saliency field of the volume V.

$$S = \{\, s_i(O,i,\sigma) \mid i \in V \,\} \tag{9}$$

Therefore we define visibility-weighted saliency field of a feature F in the volume V as ($F \subseteq V$).

$$S_F = \{\, s_i(O,i,\sigma) \mid i \in F \,\} \tag{10}$$

Then we define visibility-weighted saliency of feature F as

$$W_F(O,i,\sigma) = \frac{\sum_{i \in F} s_i(O,i,\sigma)}{\sum_{i \in V} s_i(O,i,\sigma)} \tag{11}$$

Since F is a subset of V, $W_F(O,i,\sigma)$ must be in the interval $[0,1]$. S_F can be used as a score to indicate the saliency of feature F in terms of the appearance attribute O.

Features can be defined by user-specified transfer functions or segmentation of the volume data. Figure 4 illustrates the visibility-weighted saliency fields of the three disk-like features.

3.4. Weighted Feature Saliency Histograms

As mentioned in Section 3.2, the saliency field can be computed from different appearance attributes. Multiple saliency fields computed from different appearance attributes can be combined together in order to represent different aspects of the visual saliency of voxels. In our implementation, we use brightness and saturation respectively to compute visibility-weighted saliency fields and define the weighted sum of the two sets of feature saliency as weighted feature saliency.

$$W_F = u_1 W_F(O_b,i,\sigma) + u_2 W_F(O_s,i,\sigma) \tag{12}$$

where u_1 and u_2 are weights of different appearance attributes. u_1 and u_2 are both in the interval $[0,1]$ and $u_1 + u_2 = 1$. $W_F(O_b,i,\sigma)$ is the visibility-weighted saliency of feature F computed using brightness of voxels and similarly $W_F(O_s,i,\sigma)$ is the visibility-weighted saliency of feature F from saturation of voxels.

Figure 5 and Figure 6 display bar charts of our visibility-weighted saliency of the three features and the feature visibility by Wang et al. [WZC*11] for comparison. We compute the saliency fields using brightness and saturation respectively and thus acquire two sets of feature saliency of the three features in the synthetic data set. In Figure 5 and

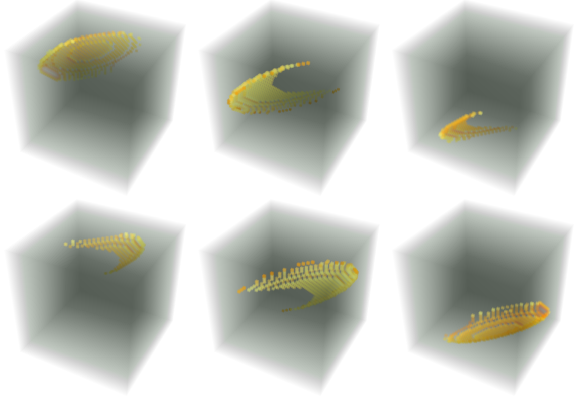

Figure 4: *Visibility-weighted saliency fields of the three disks. The first column shows the saliency fields of the top disk in the two viewpoints in Figure 1. The second and the third columns show the saliency fields for the middle disk and the bottom disk in the two viewpoints respectively.*

Figure 6, the feature saliency from brightness shows similar patterns as the feature visibility. However, the feature saliency from saturation gives the highest score to the middle disk (magenta color), which means the middle disk is significantly more salient than the other two (light green and dark green) in terms of saturation. The weighted feature saliency combines the feature saliency from brightness and saturation with user-specified weights. The weighted feature saliency can be used as a measure to indicate the saliency of features in volume rendered images. The weights of different appearance attributes should be adjusted according to the user's need in specific tasks.

4. Use Case: Measure Feature Saliency with Different Transfer Functions

In this section, we present results of using our approach to measure visual saliency of features of a volume data set with two different transfer functions.

A tooth data set [Roe06] is rendered with two different transfer functions to demonstrate the effectiveness of our approach. The first transfer function (Figure 7) assigns equal opacity to the three features. The second transfer function (Figure 10) is designed to emphasize the enamel (the yellow material), thus it assigns high opacity the enamel and low opacity to the other two features (cementum & pulp chamber and dentine).

By observation, it is clear that the transfer function in Figure 10 is better in terms of visualizing the enamel than Figure 7. The purpose of our approach is to provide an automated objective measure to make this comparison. This is demonstrated through the output of the visibility-weighted salience fields of the two transfer functions (Figure 8 and Figure 11).

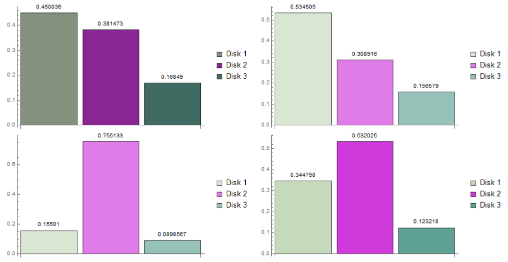

Figure 5: *The feature visibility [WZC*11] histogram at top-left shows the sum of visibility values of all the voxels belong to each feature. The two histograms of visibility-weighted feature saliency from brightness and saturation respectively (at top-right and at bottom-left) show the sum of visibility-weighted saliency of all the voxels belong to each feature ($W_F(O,i,\sigma)$ in Section 3.3). The histogram of weighted feature saliency (at bottom-right) shows the weighted feature saliency with equal weights of brightness and saturation (W_F in Section 3.4). Feature visibility (top-left) and visibility-weighted feature saliency from brightness (top-right) both suggest that the top disk is the most visible and the bottom disk is the least visible. However, the middle disk with magenta color is significantly more salient than the other two disks (light green and dark green) in terms of saturation (the histogram at bottom-left).*

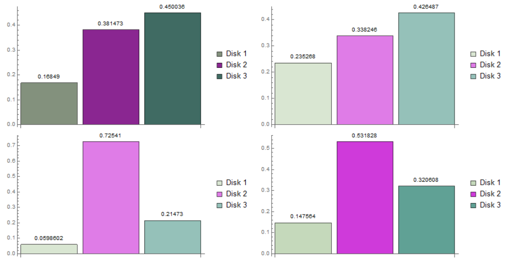

Figure 6: *Similar to Figure 5, in the viewpoint on the right in Figure 1, the bottom disk is the most visible according to feature visibility (histogram at top-left) and most salient according to feature saliency from brightness (histogram at top-right). However, feature saliency from saturation (histogram at bottom-left) suggests that the middle disk (magenta color) is significantly more salient than the other two (light green and dark green) in terms of saturation. The histogram at bottom-right is the weighted feature saliency with equal weights of brightness and saturation.*

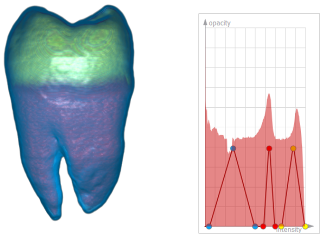

Figure 7: *A tooth data set with a transfer function revealing three features: cementum & pulp chamber (blue), dentine (red) and enamel (yellow). Equal opacity is assigned to the three features in the transfer function.*

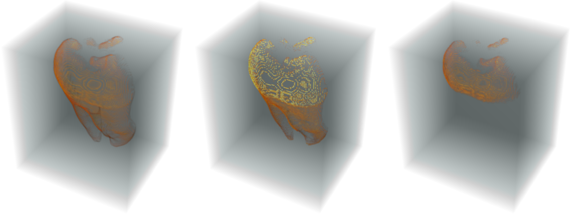

Figure 8: *Visibility-weighted saliency field of the three features, computed with the transfer function in Figure 7. From left to right, the features are cementum & pulp chamber, dentine and enamel.*

In the visibility-weighted saliency fields of the first transfer function (Figure 8), all three features are reasonably salient. On the other hand, the visibility-weighted saliency fields of the second transfer function (Figure 11) suggest the enamel has significantly higher visual saliency in the volume rendered image. The feature visibility and weighted feature saliency in Figure 9 and Figure 12 summarize the visibility and visual saliency of the three features specified by the transfer functions.

5. Conclusions

In this paper, we propose visibility-weighted saliency as an improved measure of the visual saliency of features in volume rendered images, in order to assist users in choosing suitable viewpoints and designing effective transfer functions to visualize the features of interest. With visibility-weighted saliency, the saliency of features rendered in different viewpoints with different transfer functions can be measured in a quantitative and fully automated way. In future work we plan to validate our work by conducting an eye-tracking-based user study. In addition, we would like to study other appearance attributes apart from brightness and saturation, and study the weighting between these attributes.

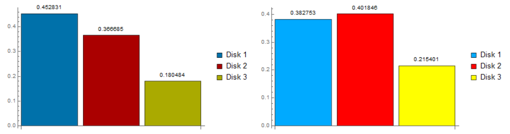

Figure 9: *Feature visibility (darker histogram on the left) and weighted feature saliency (brighter histogram on the right) of the three features, computed with the transfer function in Figure 7.*

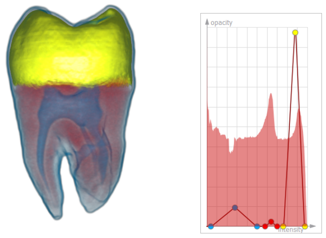

Figure 10: *A tooth data set with a transfer function particularly highlighting the enamel (yellow)*

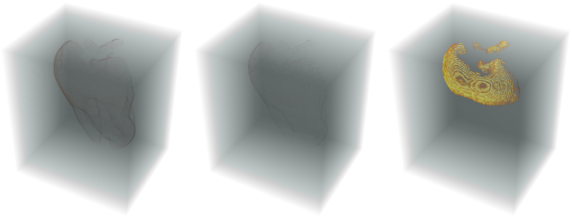

Figure 11: *Visibility-weighted saliency field of the three features, computed with the transfer function in Figure 10. From left to right, the features are cementum & pulp chamber, dentine and enamel.*

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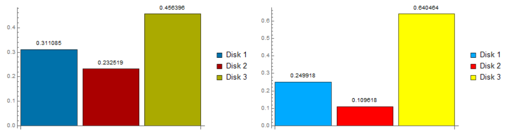

Figure 12: *Feature visibility (darker histogram on the left) and weighted feature saliency (brighter histogram on the right) of the three features, computed with the transfer function in Figure 10.*

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