Transfer Function Design for Three-Dimensional Medical Images Using Sketches

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Abstract

The visual quality of volume rendering images and the contrast between different anatomical structures strongly depends on the type of transfer function applied by the volume renderer. While conventional window-icon-menu-pointer approaches refer the user to apply pre-defined transfer functions for specific tissues, these are not always desirable for many clinical and surgical scenarios, leaving the user with the tedious and slow task of manual transfer function design. In order to make this task more natural, we propose a sketch-based interface where touch gestures are used to directly control voxel opacity and color.

We propose new transfer function design approaches that aim to reduce the number of trial and error iterations, which usually are necessary for finding appropriate transfer functions, and making them easier to use by implementing touch based gestures instead of the traditional mouse and keyboard. We present a protocol for the use of these tools, so that the user may obtain the desired results in a more optimized manner and assign color to a desired structure in an easy and rapid way. It is also offered the possibility of taking advantage of a 2D histogram, so that the user can have a better understanding of it and of the area they need to select, something that conventional approaches do not allow.

The main goal is to reduce the amount of time and effort which usually are necessary for finding the appropriate transfer functions, and allow for a rapid exploration and a better overall understanding of the volume data.

Keywords

Transfer Function, *Volume Rendering, 3D Medical Images, Sketch-based Interface*

1. INTRODUCTION

With the massive amount of information available about the human anatomy it can became a chore to properly organize and display this information in a comprehensive and well-structured manner, so that it can be used effectively in both a scientific and medical context. (Mathematics, 2012)

Since internal structures of the human body are not generally visible, Medicine takes advantage of images acquired by Computed Tomography (CT), Magnetic Resonance Imaging (MRI), Positron Emission Tomography (PET), Ultrasounds, so that it is possible to achieve a precise and scientifically accurate visualization of medical data.

To aid in this process, volume rendering of 3D medical images is often used in several healthcare contexts, but the visual and graphical quality of the rendered image along with the contrast between anatomical structures strongly depends on the type of transfer function that is applied by the volume rendering engine. While conventional software allow users to apply pre-defined transfer functions, usually intended for isolating specific tissues, these are not always desirable or even possible for many clinical or surgical scenarios, requiring the user to design these functions through a WIMP interface, which is a tedious and time consuming task. When the interface is heavily dependent on the window-icon-menu-pointer (WIMP) approach or requires a long sequence of actions to obtain a desired result.

A large number of users have difficulties in understanding large sets of data and identify what they are looking for within those sets, especially if these users do not have the appropriate background. It has been shown that many users of interactive volume rendering software do not have the required visual skills/expertise necessary to obtain the desired results in a timely manner or with the best quality. (Praßni and Ropinski, 2009) (Arens and Domik, 2010) Thus, simple techniques to explore, manipulate and modify these data sets are required.

In this thesis we propose a new sketch based approach for designing transfer functions with an interactive application, developed for this purpose, called Voxel Tips. These new approaches rely on an interactive surface, where touch gestures are used to directly sketch the transfer function that controls voxel opacity and color, and manipulating the volume data by changing its position and orientation using familiar and easy to learn gestures. New sketch-based tools are also presented with the goal of reducing the number of trials-and-errors necessary to find an appropriate transfer function and allowing a better understanding of the volume data.

2. BACKGROUND

2.1 State of the Art

Conventional volume rendering software such as Voreen, OsiriX, Votracer, Paraview and others (OsiriX, 2015), (Paraview, 2015), (Votracer, 2015), (Voreen, 2015) follow a WIMP approach and allow for interactive visualization of volume data sets. They offer some tools that allow easy identification and characterization of structures through the design of one-dimensional transfer functions or from the selection of a predefined transfer function from a predetermined selection. Along with these tools, simple geometrical transformations such as rotation and translation are possible using mouse controls.

Design of the transfer function is usually done by manipulating the position of several cursors over a canvas which, once connected between them by a straight line, form a ramp-like function, although it may also be achieved by directly designing the function using the mouse, such is the case with Votracer. This function serves as the transfer function that controls the opacity of the voxels in the data set.

In these approaches, color is assigned either to the same cursors or to a new set of cursors that work in a similar fashion, with the color between cursors defined as an interpolation of the colors of the nearest neighbors.

2.2 Problem Statement

When dealing with images acquired by CT we can apply standardized transfer functions that allow us to quickly isolate features of interest. However, if the anatomical structure of interest is not well isolated in predefined transfer functions, or if the images to be used were acquired by MRI, users have to design their own function.

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2.2.1 Trial and Error on Transfer Function Design

One of the major reasons for the amount of trial and error associated with the design process is the users' lack of ability to determine the correct relationship between the domain of the transfer function and the data of the volume, leading the user to design the transfer function "blind". Thus, better ways are necessary for providing the user feedback about the information contained in the domain.

2.2.2 User Interface Complexity

Another limitation present in the traditional volume rendering software is the fact that the tools used to design the transfer function are sometimes difficult to learn because of a complex and large number of commands, displayed in what is usually a cluttered and confusing user interface. Even when the correct tool is used, the design of the transfer function is not fluid or easy to perform, often requiring a large number of small steps to obtain the desired shape of the transfer function, moving each individual cursor one at the time, or employing very simple and yet very limiting controls.

2.3 Background Definitions

2.3.1 Medical Image

Image acquisition methods such as Computed Tomography (CT) and Magnetic Resonance Imaging (MRI) have allowed us to obtain non-invasive images of the human body. These image acquisition methods produce 2D slices of the human body. To make storage of this data possible in a computer, the image must be divided into smaller sections called picture elements, or "pixels". For each pixel is assigned a single numerical value (intensity value) that assigns the shade of gray, in case in dealing with images acquired by CT or MRI. By assigning gray levels to different ranges of intensities, a grayscale image can be produced.

2.3.2 Volume Data and Volume Rendering

A 3D volume consists on a set of 2D images acquired by MRI or CT.

In order to create a volume rendering based on these images we need to store their information in a data volume. A data volume can be defined as a regular 3D array of data values, which represent voxels. Volumetric data is typically a set of samples representing the value of some property of the data, at a 3D location. (Peng et al., 2010)

Once the volume data is defined a 2D display of the 3D data is created on the screen. This 2D representation is achieved through one of several volume rendering techniques. Of these techniques, Ray Casting is one the most used and the one with the largest number of publications and research done on the subject. (Report and Zhou)

In Ray Casting, rays are cast from the view point of the display and into the volume in virtual space. Once the ray intersects a voxel, it is evaluated according to the applied transfer functions and its contribution to the 2D display is computed. Each ray is casted from a single pixel on the screen and the final contribution determines the color of that pixel. The contribution of each voxel is usually defined by the opacity and color attributed to that voxel, with several voxels having the possibility to contribute to the same pixel. Once the contribution of each pixel is computed an image is displayed on the screen representing the rendered volume based on the volume data. (Report and Zhou)

2.3.3 1D Transfer Function

When information from the 2D image slices is used to create the volume data it becomes necessary to define the optical properties associated with each voxel. This is achieved through a transfer function that applies the Red, Green, Blue and alfa color components to the corresponding voxel of the volume. This is what we call unidimensional transfer function. It controls which voxels with a certain intensity value are visible and how much opacity they contribute to the final volume, in such a way that only important features should receive high opacity, so as to not to be obscured by the opacity from other non interesting regions.

A histogram is used so that simple information is presented to the user. A scalar histogram shows the way that scalar data is distributed all over the entire scalar domain. However, it does not give spatial information to the user, leading to a trial and error process to achieve the desired transfer function. However, it does not allow to discriminate features within a data set which have an overlapping intensity range of the data, which raises the demand for a 2D transfer function.

2.3.4 1D Gradient Transfer Function

The magnitude of the gradient of the intensities of each voxel allows for the distinction between homogeneous regions and their transition regions, which it is extremely useful in a medical context when the feature of interest is between two homogeneous materials, i.e., to display surfaces of features. Tissues that are relatively homogeneous present low gradient magnitudes, while heterogeneous tissues present high gradient.

2.3.5 2D Histogram

A boundary model is used in the form of an intensity-gradient histogram, which can be used to inform the user about the location of boundaries within the data. It maps each data value to a specific intensity and gradient value, applying to each a color and opacity. Thus, it is able to differentiate between samples that share the same intensity range but are located in different neighborhoods. They can be seen as the circular regions at the bottom of the histogram. The boundaries between these tissues are represented as arc-like shapes connecting each circular region. (Varshney and JaJa, 2012) Each of these tissues and boundaries can be isolated using a 2D transfer function based on intensity value and gradient magnitude.

2.4 Related Work

Several other research projects have looked into these problems and several possible solutions have been explored and documented.

Liu, Bingchen et al have explored an approach that aims to allow inexperienced users to acquire meaningful three-dimensional visualizations. This approach takes advantage that when two relatively thick materials have a thin transition region or if two materials have distinct densities we call that region a boundary and when represented in a histogram the result is the materials forming a peak and the transition region forming a valley. For each peak an unit transfer function is defined, capturing only the region on that part of the histogram and for each unit transfer function a random color and an opacity value are associated with that peak. These visualizations are presented in order to allow the user to access and select the desired ones and put them together so that more complex visualizations can be achieved taking advantage from user’s domain knowledge. (Liu, Bingchen et al,2010)

Sereda et al proposed a new process, in which users can efficiently identify materials that form boundaries. To do so, the boundary classification is performed with a LH histogram, instead of a transfer function based on scalar values. We can use a 2D transfer function based on the LH Histogram through the selection of the areas of interest, with the possibility of assigning to them optical properties. The spatial information, contrary to other approaches, is also taken into account such that a neighbor that is similar to an already labeled voxel is labeled similarly, allowing the region to grow. This is performed through a cost function that measures the similarity so that the region could be extended to that evaluated voxel.In this approach, it is possible to select boundaries that would otherwise be difficult to isolate using 2D histograms, since the arches representing each boundary often overlap. (Šereda et al., 2006)

3. METHODOLOGY

This thesis is based on the proposition of a new interface based on sketches, in which is given to the users the ability to freely design their own function on an interactive surface, with the aim of reducing the number of iterations, trial and error, so typically associated with any design process that uses WIMP approach. The interface offers features that allow for a quick recognition and general exploration of intensities in the function domain and the anatomical structures related to them.

3.1 Voxel Tips

Voxel Tips consists on a new interface based on sketches, in which is given to the users the ability to freely design their own function on an interactive surface, with the aim of reducing the number of iterations, trial and error, so typically associated with any design process that uses WIMP approach. The interface offers features that allow for a quick recognition and general exploration of intensities in the function domain and the anatomical structures related to them.

3.1.1 Tridimensional Representation

The representation of volumes is based a 3D texture that is composed of voxels. These texture voxels are used to store information derived from 2D images, so that it is possible to observe the information contained in those images but in a three dimensional representation.

The representation of thumbnail volumes is based on a particle-based volume rendering. It represents a volume as a set of emissive and opaque particles that will store the information derived from 2D images.

3.1.2 Geometric Transformations

The manipulation of the volume data is made exclusively for multi touch gestures. Dragging one finger across the touch surface, the user can turn the volume in any direction, and the rotation will follow the fingers movement. Using two fingers, the user is able to zoom in or out (moving the fingers away from or toward each other, respectively)

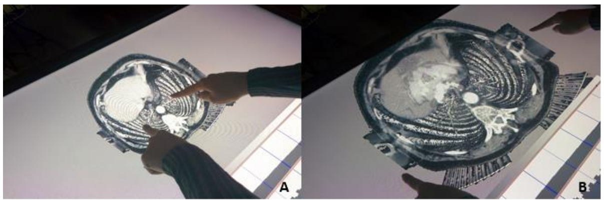

Figure 1. Moving the fingers towards each other the user is able to zoom out (A) and away from each other is able to zoom in (B)

To assist volume manipulation, there is also an open box in the lower left corner that allows for the visualization of the volume from a given perspective, according to the direction of the cube's faces

3.1.3 Transfer Function

In the specific case of medical imaging, each voxel would have associated an image intensity value, which is used as input. When dealing with gradient functions, the magnitude of the gradient of the intensity of each voxel is used as an input instead.

The final transfer function applied to the volume results from the combination of the intensity and gradient, i.e., the product between the two. The transfer function is then applied to the volume.

To accompany the transfer function a histogram is presented on the screen background. This histogram is a graphic representation of a distribution of data, representing the number of voxels present in the volume having a given discrete value of the field, with this field being limited by the maximum and minimum intensity of the voxels in the data.

When designing transfer functions over the 2D histogram, the function domain is represented by a matrix, with resolution defined by the discretized values of the intensity and gradient domain (a [intensity domain x gradient domain] matrix). Each point in the matrix describes a voxel with the corresponding intensity and gradient values. When a selection is made, points within the selection are defined in the matrix a 1 and grant the corresponding voxels full opacity, while points outside the selection are defined by 0, with full transparency of the voxel.

3.1.4 Plataform of Function Design

The user interface consists of a table of large dimensions, arranged horizontally, where the users can perform the visualization of data. There is a multi-touch sensor system on the table, responsible for the user's contact detection with the surface. In this multi-touch sensor system, the touch is detected through an array of infrared sensors that determine the position of each touch when infrared beams are blocked.

The drawing area consists of two white screens, divided into ten segments, on which the transfer functions will be arranged and designed. There are also two grayscale bars above and below the white screens, as well as a set of thumbnails on the bottom of the screen, whose functions are described later in the chapter. There is also a set of buttons directly to the left and the right of the white screens that allow users to select the various wanted features. The menu on the left selects tools for the intensity function, while the menu on the right selects tools for the gradient. These buttons are for the following features: the ramp-like, sliding window, multiple sliders and a sketching tool, respectively from top to bottom.

3.1.5 Unity 3D

The main application was developed using the Unity3D engine and run with Windows 7 operating system. Unity 3D is fairly well documented in terms of tutorials, as well as C # language that has an extremely well documented library. Furthermore, given the versatility of Unity 3D this makes it ideal because of the huge number of features that can be implemented when compared to traditional software, which are much more difficult to develop because of limited and often poorly documented libraries and the lack of available development tools and experience.

3.1.6 Transfer Function Design

The new set of tools proposed by Voxel Tips is applied on a rectangular white screen. These screens have displayed in their background the histogram that represents the analyzed data, and are divided into 10 equal segments, each representing 10% of the transfer function area. This separation serves to assist the user in the interpretation of the histogram data and serves to complement the proposed functionalities. The following tools aim to make the design process more personal in such a way that after the inspection of the domain and the identification of which areas of the transfer function domain the user is going to assign opacity to, the user has the opportunity to manually sketch the transfer function. The isolation of features of interest relies on the user's domain inspection.

3.1.6.1 Thumbnails

In order to provide a comprehensive description of the data in the way that allows an immediate insight of the main structures in the data set, a set of thumbnails are arranged below the screen. Each thumbnail represents 10% of the area of the transfer function, facilitating both the transfer function design as well as the interpretation of the histogram data. This feature compensate the lack of spatial information associated with the one-dimensional transfer function, creating a direct and visual relationship between the intensity domain and the volume data.

3.1.6.2 Ramp-like Function

The ramp-like function is typically found in most data visualization software like Osirix, Volview, Voreen and Exposure Render. The function is defined by the user. which can be moved vertically between the top and bottom of the screen. The intermediate values between the two nodes are determined by linear interpolation, similarly to the traditional software.

3.1.6.3 Sliding Window

The sliding window allows for the exploration of the domain of the transfer function, by allowing the user to highlight the desired domain interval and explore the volume structures present within. This window behaves like a quadratic signal with the values of the function domain contained within the window boundaries set to a certain opacity value and the remaining function values set to zero. The selected interval has an opacity value proportional to the height of the window itself, with maximum height corresponding to one and minimum height corresponding to zero. The window height and width can be easily adjusted by dragging two cursors on their upper limits and the maximum height and width are limited to the screen dimensions.

3.1.6.4 Multiple Sliders

Each segment of the divided screen represents 10% of the transfer function domain, superimposed by a semi-transparent slider that represents each section. Each slider can be dragged or positioned at any height within the screen, wherein the position of the sliders superior limit is the opacity to be assigned to the function values within the range of that slider. Several sliders can be moved simultaneously and thumbnails themselves can be used as buttons to reduce the opacity of the corresponding range to zero or switch the interval opacity between zero and one.

3.1.6.5 Sketching

The user is given the option to freely draw any figure on the screen. Once drawn, this outline is adapted and transformed into a direct transfer function applied to the volume and the resulting function is represented on the screen, replacing the previous one. The function can be modified in any way by the user, along any length of the domain.

3.1.6.6 Color Assignment

Two grayscale bars are positioned directly above and below the white screens. The assignment of colors is done interacting with the top bar: when a double-tap is performed this bar will create a small cursor that has a given color, assigned through a color picker. Pressing the cursor once opens or closes the color selection screen. The selected color is applied to the cursor in real time and the color is assigned to the volume.

3.1.6.7 Gradient

Additional information such as the gradient helps the user distinguish between tissues that close to their boundaries and those who are located more internally. In order to map the gradient magnitude to opacity, the same architecture used in 3.1.6 was used as well as the domain inspection tools in order to reduce the trial and error in the design of the desired transfer function. To obtain the gradient magnitude a 3D Sobel operator was used. (CS 788H S01 Project - Gradient Estimators, 2015) The 3D Sobel operator performs a 3D spatial gradient measurement where a 3x3x3 kernel is used to compute each of the partial derivatives.

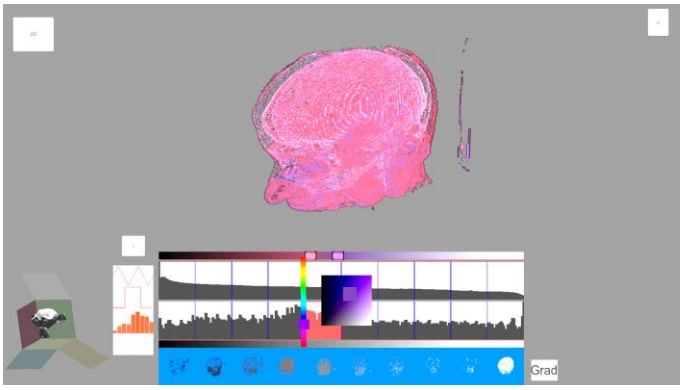

Figure 2. Voxel Tips interface with the screen for 1D intensity and gradient transfer functions design. The tools proposed in this thesis appear on the left of the screens.

3.1.7 Usage of the transfer Function

It is important to not only determine which features to use, but also in what order they should be used. Thus, it has been determined that manipulating the representation should be made so that it never transits from a functionality with greater information to one of lower information, resulting in a succession of tools depicted in Figure 2. This selection of tools can be applied independently to the intensity and gradient transfer function.

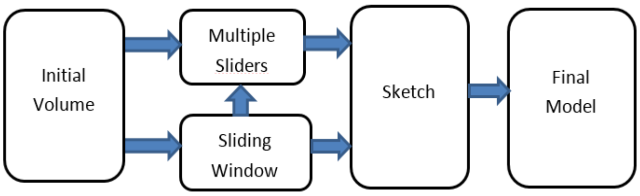

Figure 2. Sequence of tools propose to design the intensity and gradient transfer function.

3.1.8 2D Histogram

A screen is used to display a 2D histogram. . In order to create a familiarity with the 1D transfer function design (intensity function 1D and gradient 1D), the screens of the intensity function and the gradient function are displayed horizontally and vertically to the 2D histogram. There is also a color assignment to the gradient contribution, discussed in 3.1.6.6. The user performs area selection manually by drawing the perimeter of the desired selection area. The area is defined once a collision of the line is detected and thus the area is closed. All points within the selection are attributed maximum opacity and points outside the selection are assigned a zero opacity. In order to detect which points are within the selection, an algorithm based on the Jordan Curve Theorem (Hales, 2007) was used.

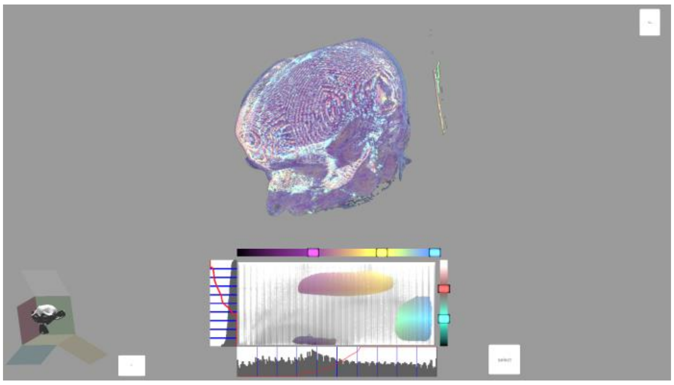

Figure 3. 2D histogram

4. USER TESTS

A series of tests have been conducted in order to evaluate the interface developed with the main goal of obtaining information about the gains and limitations that Voxel Tips may possess in the design of transfer functions. The user tests were carried out using three anatomical structures, wherein for each one, an image was presented of the desired result that the user would have to obtain using the tools provided by the interface and their performance was measured by taking into account the time they needed to complete each task. One volume was used as a training volume (test 1) while the other two were used to measure the time of completion. The tests were performed on two interfaces: Votracer (Votracer, 2015) which was chosen due to its similarity to both traditional software and the interface developed along this thesis: Voxel Tips.

The tests consists in presenting an image of the desired result which the users where asked to obtain by manipulating a single function, such as intensity, gradient and 2D histogram, presented in this order. Each task was timed for all users during tests 2 and 3 and the number of attempts was determined for a number of test subject. In order to avoid familiarity with the data set from influencing the final results, the interface which the user would perform the tests first was chosen randomly.

5. RESULTS

The tests were carried out with 15 people, aged 19 to 24 years (m=21,87; sd= 1,73) all belonging to Engineering courses (Bachelor or Master). From these, 10 were men and 5 were women. All users had devices with touch controls and used them several times a day (>5 times a day). Before the tests, some of the users already had basic no-

Fig

tion of medical imaging and others did not have experience with medical images.

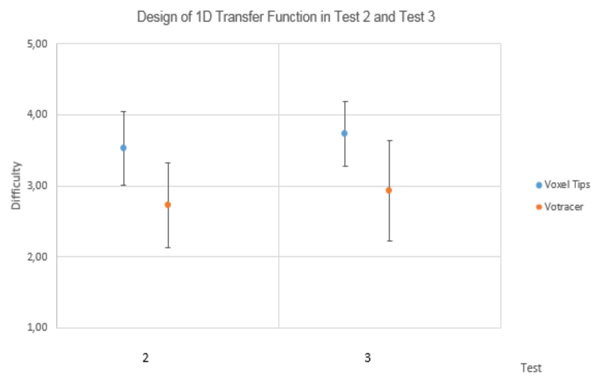

Figure 5. Difficulty in the design of 1D transfer function in test 2 and Test 3

When comparing the difficulty felt when designing the transfer functions, users found that Voxel Tips was easier to use to obtain results in both the first and second test (m=3,53, sd=0,52; m=3,73, sd=0,46, respectively), when compared to using Votracer (m=2,73,sd=0,59; m=2,93, sd=0,70 respectively). Overall, users found Voxel Tips easier to use (m=3,80,sd=0,74), when compared to Votracer (m=2,40, sd=0,74) and overwhelmingly prefer the tools presented in Voxel Tips for the design of 1D transfer function (100%), gradient function (100%) and 2D histogram (87%).

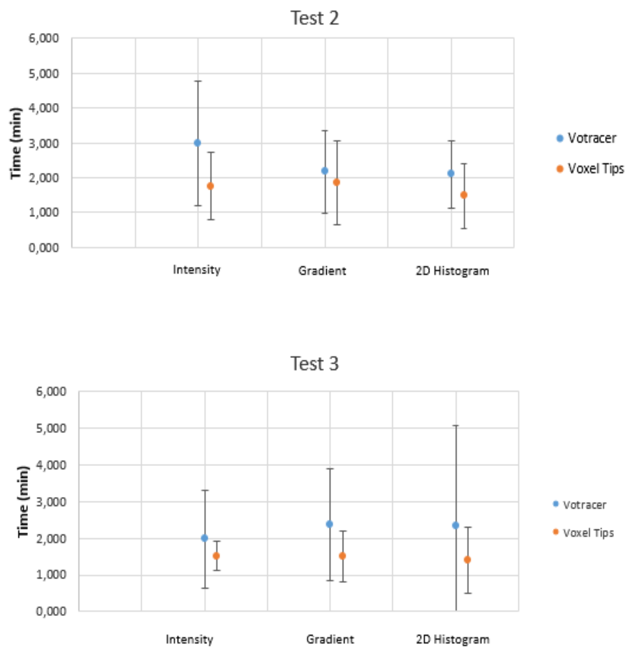

Figure 5. Users performance in both interfaces in test 2 and test 3, respectively

In order to evaluate users performance in both interfaces, the data from the that users spent performing each task was gathered and compared in order to determine in which interface users can achieve the desired result in the least amount of time. (Figure 3) When comparing users performance in both tests, we can observe that there is a decrease in the time that is necessary to obtain the transfer function of the intensity, gradient and the 2D transfer function while using Voxel Tips when compared to Votracer.

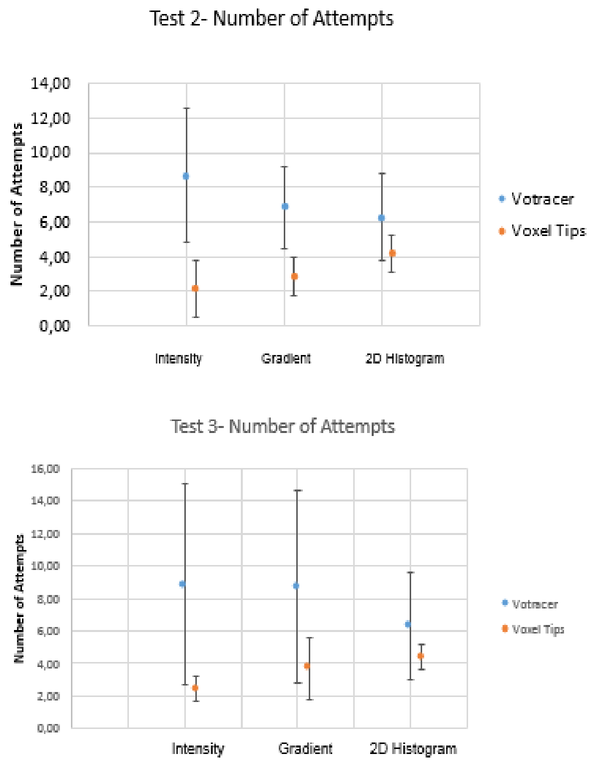

Figure 6. Number of attempts necessary to perform each task in test 2 and 3, comparing the results between both interface

A paired t-test was performed to determine if the time users needed to perform each tasks were significantly different.

The mean number of attempts to design the intensity transfer function in Voxel Tips (m=2.43, sd= 0.79) was significantly inferior when compared to Votracer (m=8.86, sd=6.15), paired t(6)=2,92 , two-tail p = 0.027. A 95% Confidence Interval (C.I.) about the mean number of attempts is (1.03, 11.82).

The mean number of attempts needed to design the gradient transfer function and the 2D transfer function were not significantly different between interfaces.

The mean number of attempts to design the intensity transfer function in Voxel Tips (m=2.71 ,sd

=0.95) was significantly inferior when compared to Votracer (m=8.86, sd=6.15), paired t(6)=2,85 , two-tail p = 0.029.A 95% C.I. about the mean number of attempts is (0.87, 11.41).

The mean number of attempts needed to design the gradient transfer function in Voxel Tips was not significantly different between interfaces.

The mean number of attempts to design the 2D transfer function in the 2D histogram in Voxel Tips (m=4.14, sd =1.07) was significantly inferior when compared to Votracer (m=6.29, sd=2.50), t(6)=2,79 , two-tail p = 0.032. A 95% C.I. about the mean number of attempts is (0.26, 4.03).

The number of attempts have a much greater variability in Votracer, which may indicate the influence of the random element when obtaining the transfer function.

6. DISCUSSION

Through the analysis of the data we can observe that users performed better when using Voxel Tips, rather than Votracer, which is mainly due to the simplicity of the interface and the existence of a set of tools that allow for the inspection of the transfer function domain. This gives users a better understanding of the data set and its relationship with the function domain, since both the sliding window and multiple sliders tools limit interaction to specific ranges in the domain. There is also a reduction of the number of attempts related to the trial and error procedure and a reduction of the random elements associated with the transfer function design, which is mainly due to the fact that user interaction is more restricted in the domain resulting in a more methodical interaction, which makes designing a transfer function less of a trial and error approach and more a step by step procedure.

The presence of thumbnails that visually described the information present in the transfer function domain have proved to be one of the most helpful tools present in Voxel Tips. Since this tool is able to easily and quickly provide information to the users about the transfer function domain they contributed heavily to the decrease of the time necessary to design the intensity transfer function. This becomes more apparent when we look at the performance of the gradient transfer function design, which was slower than the design of the intensity function, despite having all the same tools except for the presence of the thumbnails.

The lack of significant results when designing the gradient transfer function may indicate that users still have noticeable difficulties understanding the function domain. This was apparent for users of all backgrounds, which means that new or improved tools may be necessary to better understand how the gradient domain is related to the volume data.

During tests, users complained about the way Votracer handled the design of the transfer function, finding it difficult to use with a mouse, and much preferred the use of touch controls for the transfer function design. The users overwhelmingly preferred touch interaction to perform the tasks, which can be explained by the fact that gestures do a better job at translation users intentions, when compared to the traditional WIMP approach using a mouse. (Wang et al., 2013)

When dealing with 2D histogram selection, Votracer allows an easier exploration when compared to Voxel Tips. In other hand, Voxel Tips data selection and deselection is slightly easier to perform than that one found in Votracer as well as being much more versatile, allowing for the selection of any area of the domain, not being limited to geometrical shapes. However, the lack of a proper exploration tool may be a limitation that limits Voxel Tips and may have kept it from performing better.

In the selection of structures in 2D histogram, the color proved to be an useful tool, contributing to the better performance of Voxel Tips when dealing to the 2D histogram. This is because the colors attributed to the domain of intensity and gradient was displayed in the selection made by users, making the mapping of data easier since users could determine which areas to select and deselect based on the color of the domain.

Overall, Voxel Tips obtain positive results, being able to mitigate many limitations observed in several approaches that are currently used today to deal with volumetric data.

7. FUTURE WORK AND CONCLUSIONS

7.1 Future Work

New ways of selecting and assigning colors to the intensity domain should be the subject of future research work. The intensity color bar could be eliminated and the color grading would be applied directly to the intensity histogram. This would promote a quicker understanding of the information and also a more minimalistic environment with less cluttering in the area of interaction.

One limitation of transfer function design with the 2D histogram in Voxel Tips is the inability to freely and fluidly explore the volume data in the function domain, unlike Votracer and other volume rendering software.

A hybrid between the functionalities of Votracer and Voxel Tips would be of great value, where the user would be able to draw any polygonal shape on the canvas and freely move it around the domain, giving them the ability to explore the volume data in a simple and versatile manner. Taking advantage of the tools implemented in the present interface, one improvement can be made by the combination of the sliding window tool and the thumbnails.

Instead of the current thumbnail display with ten thumbnails, we can have a single thumbnail that can navigate through the domain, similarly to the sliding window and display only the points, whose intensity is within the range of the thumbnail, giving users the ability to inspect limited intervals of the domain, regardless of any function applied to the current volume.

This thumbnail can also be used to add step function to the domain when double clicked, improving on the functionality of the sliding window, which can only have a single step function present.

7.2 Conclusions

To achieve an adequate visualization of volume data, a proper transfer function design is required, which is not easy to achieve. Despite some approaches focusing on aiding the user in the transfer function design, there are still some gaps and limitations that need to be conveniently addressed, namely the fact that many of these approaches use multidimensional transfer functions to achieve results, which makes the users job more difficult, since the higher the dimension of the transfer function, the higher the complexity of specifying it.

Simpler approaches often rely on a single dimension and limit the users' interaction and customization of the final transfer function. This creates a need for an approach that increases users' knowledge of the data domain and gives them the necessary tools to customize the design of the transfer function.

To deal with these problems, Voxel Tips offers users a new set of tools that proved to be efficient when dealing with the design of intensity transfer functions.

It was shown that users prefer Voxel Tips, which takes advantage of a touch interface and gestures, instead of the conventional software that takes advantage of WIMP approach and mouse controls.

The tools presented, which focus on function domain exploration and sketching of the transfer function served to decrease the number of trial and error iterations needed while increasing users understanding of the volume data and its relationship with the transfer function domain.

Voxel Tips showed to be a versatile and user friendly interface, which opens up a wide range of possible applications in several areas, not all of them limited to medical data, while still accessible to a variety of users with different backgrounds.

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