Transfer Function Design for Three-Dimensional Medical Images Using Sketches

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"Ninguém escapa ao sonho de voar, de ultrapassar os limites do espaço onde nasceu, de ver novos lugares e novas gentes. Mas saber ver em cada coisa, em cada pessoa, aquele algo que a define como especial, um objeto singular, um amigo,- é fundamental. Navegar é preciso, reconhecer o valor das coisas e das pessoas, é mais preciso ainda." Antoine de Saint-Exupery

RESUMO

A qualidade visual imagens volumétricas e o contraste entre estruturas anatómicas diferentes depende fortemente do tipo de função de transferência aplicado ao volume. Enquanto as abordagens convencionais baseadas em janela-ícone-menu-rato permitem ao utilizador aplicar funções de transferência pré-definidas para o isolamento de tecidos específicos, estes nem sempre são desejáveis para muitos cenários clínicos e cirúrgicos, delegando ao utilizador a tarefa entediante e morosa do design manual função de transferência. A fim de tornar esta tarefa mais natural, propomos uma interface baseada em esboços onde o toque é usado para controlar diretamente opacidade e cor do voxel.

Propomos novas abordagens de design de funções de transferência que visam reduzir o número de tentativas e erro, que geralmente são necessárias para encontrar funções de transferência apropriadas, e torná-las mais fáceis de usar recorrendo a toques em vez do tradicional rato e teclado. Apresentamos também um protocolo para a utilização destas ferramentas, de modo a que o utilizador possa obter os resultados desejados de uma forma mais optimizada e atribuir cores às estruturas desejadas de forma fácil e rápida. É também oferecida a possibilidade de tirar proveito de um histograma 2D, para que o utilizador possa ter uma melhor compreensão do mesmo e da área que precisa selecionar, algo que as abordagens convencionais não permitem.

O objetivo principal consiste em reduzir a quantidade de tempo e esforço, que normalmente são necessários para encontrar as funções de transferência apropriadas, e permitir uma exploração rápida e um melhor entendimento geral dos dados de volume.

Palavras-chave: *Funções Transferência, Renderização de Volumes , Imagens médicas 3D, Interface baseada em Esboços*

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*

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LIST OF SYMBOLS

∇f	Gradient
$\frac{df}{dx}$	partial derivative of f in x
$\frac{df}{dy}$	partial derivative of f in y
$\frac{df}{dz}$	partial derivative of f in z
e1	vector with the direction of the first dimension (1,0,0)
e2	vector with the direction of the second dimension (0,1,0)
e3	vector with the direction of the third dimension (0,0,1)
G*x*	magnitude of the gradient of x
G*y*	magnitude of the gradient of y
G*z*	magnitude of the gradient of z

GLOSSARY

CI	Confidence Interval
CT	Computed Tomography
MRI	Magnetic Resonance Imaging
PET	Positron Emission Tomography
SBI	Sketch Based Interface
TF	Transfer Function
WIMP	Window,Icon, Menu, Pointing Device

CHAPTER I

1 INTRODUCTION

1.1 MOTIVATION

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. In the latter, this is especially important since a correct interpretation of the data is often required for important decision making in both diagnosis and other medical procedures. (Adeel, 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. Thus, it is possible to observe and explore in detail the internal organs/ tissues of the human body as well as study the process of human illness and injury. 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, which attribute optical properties to the data, these are usually intended for isolating specific tissues, and 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.

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.

Currently available software, like OsiriX, Volview, Voreen, follow a Windows-Icon-Menu-Pointer (WIMP) approach and have some tools that allow for easy identification and characterization of structures. (OsiriX, 2015) (Voreen, 2015) (Volview, 2015)

Transfer functions are inherently non-spatial (i.e., neither the function domain nor its range are geometrical quantities) which increases the difficulty of showing specific anatomical structures, since while they are easily characterized by their geometrical location, they are not readily distinguishable in terms of voxels' intensity. (Kindlmann, 2002) These applications have a histogram associated with the transfer function, which has information regarding the distribution of data in the intensity domain of the data associated with the anatomical structure. Since the histogram does not have spatial information and the transfer function lacks it as well, this hampers the user's task to associate the transfer function's domain to the anatomical structure of interest. Achieving a meaningful and intelligent volume rendering is one of the most important tasks of a volume rendering software, but it is difficult to achieve. When dealing with CT images, conventional software can apply standardized and pre-defined transfer functions that allow us to quickly isolate features of interest. However, if the anatomical structure of interest is not isolated by predefined transfer functions or if the images to be used were acquired through MRI, it will lead to a strong interaction based on trial and error by the user, as he/she attempts to define the transfer function manually using several clicks. It is noteworthy that predefined transfer functions may not be properly optimized and may require further manipulation. (Freiman et al., 2007)

Several studies have focused on automatically creating or adjusting the desired transfer functions, (Vega Higuera et al., 2004) adapting them to characteristics present in the data or modifying the approach in order to present a user interface more suitable to the iterative design process of functions, (Liu et al., 2010) but without changing the way the function is designed.

In addition to the manipulation of transfer functions, studies have also been conducted with the aim of providing prior information about the data without the need for complex multidimensional functions. It has been shown that the higher the dimension of the transfer function, the higher is the complexity of specifying it. (Maciejewski et al., 2012) Even 2D transfer functions require a lot of user interaction so that a meaningful specification can be found.

Currently available software that allow for the isolation of features follow a Windows-Icon-Menu-Pointer approach. In this thesis, a touch-interaction is explored to confer direct control of the transfer function design and geometrical transformations as the WIMP approach presents a greater separation between the users intent and the end result. (Isenberg, 2011)

This thesis aims to present evidence that giving the users the ability to freely design their own function on an interactive surface will reduce the number of trial and error that are so typically associated with any design process that uses WIMP approach. When applying these tools, users were able to explore and understand the volume´s data more easily, reducing the number of attempts necessary to obtain a desirable function.

1.2 Objectives

The main objective of this thesis is to study new ways of effectively designing transfer functions trough sketches. In order to achieve this objective a new interface based on sketches was developed, giving the users the ability to freely design their own function on an interactive surface. It offers a reliable and efficient set of tools that allows for a quick exploration and interpretation of intensities, gradients and how their domain is related to anatomical structures, with the main goal of reducing the number of trial and error. In order to accomplish these objectives the following goals are addressed:

- Obtain a rapid and effective exploration / manipulation of medical volume.

- Develop new sketch-based tools to reduce the number of trials-and-errors necessary to find an appropriate transfer function through the improvement of user's understanding of the data (intensity and gradient), making use of a surface interface, where touch gestures are used to directly control voxel opacity and color by sketching transfer functions.

- Use color assignment as a simple and natural way of visually distinguishing structures.

- Implement a 2D histogram interface, in such a way that allows the user to isolate structures that are located between heterogeneous tissues, i.e., boundaries.

- Determine which is the best way for users to define the 2D transfer function: Through the intensity and gradient functions (through the sketch-based tools that allow the user to understand the transfer function domain) or by the 2D histogram.

- Show how this interface would be useful in a medical environment, in scientific illustration and in medical education.

1.3 Thesis Outline

This thesis presents a set of tools that allow users to obtain the desired results and assign color to structures. The main goal is to reduce the amount of time and effort necessary to find appropriate transfer functions, so that a rapid exploration and a better understanding of the volume data can be achieved.

In the next chapter, some fundamental concepts related with this work are explained so that all the issues addressed in this thesis can be understood. This also serves as a basis for some other approaches that tried to address the same problem, which are also explored in this chapter. When considering these approaches, an analysis of some important limitations is performed, so that a solution for each of these drawbacks can be designed.

In Chapter 3, the drawbacks verified in each approach will be considered and taken into account in the design of a new set of tools, developed to deal with some of the limitations. A description of each of these tools will be presented along with its purpose.

In Chapter 4, an outline of the user tests is performed, highlighting the purpose of each test and how user performance was evaluated.

In Chapter 5, the results obtained in the user tests will be presented and analyzed.

In Chapter 6, a discussion of the results presented in Chapter 5 will be performed, along with a collection of professional opinions and feedback regarding Voxel Tips, so that a proper conclusion about the value of this new set of tools can be achieved.

In Chapter 7, the discussion of user tests results as well as the professional medical opinions will be taken into account to delineate some improvements and future work, so that an interface suitable for medical and educational environments can be achieved, followed by a final conclusion of this thesis.

1.4 Contributions

The contributions of this thesis extend to a large variety of areas, due to having a versatile nature. Some of the contributions are:

- An interface that minimizes the number of trial and error associated with the 1D transfer function design.

- New and more customizable ways of selecting and interpreting data in a 2D histogram.

- A set of tools that allows the users to inspect the transfer function domain and optimize standard transfer functions.

- Making the distinction between structures easier and more comprehensive in medical volume data.

1.5 List of Selected Publications

1.5.1 National Conferences

- **Parreira, Pedro; Mendes, Ana Rita; Simões, Daniel Lopes; A. Jorge, Joaquim (2015)** Design de Funções Transferência para Imagens Médicas 3D recorrendo a uma Interface baseada em Esboços, SciTecIN'15 - Ciências e Tecnologias da Interação, Coimbra, Portugal.

CHAPTER II

2 DEFINITIONS AND RELATED WORK

2.1 FUNDAMENTAL CONCEPTS

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. For each pixel in these slices it is assigned a single numerical value (intensity value) that defines the shade of gray, in case of dealing with images acquired by CT or MRI. By assigning gray levels to different ranges of intensities, a gray-scale image can be produced. This represents various structures in the patient with different x-ray attenuation characteristics (CT) or proton density (MRI).

Figure 1 - Liver acquired by Computed Tomography (CT). (Wikipedia, 2014)

In CT, images are acquired with a machine that emits and detects X-rays that are attenuated as they pass through matter (Figure 1). This means that the intensity of an X-ray beam decreases the further it penetrates into the human body. The decrease in intensity of an X-ray beam depends of two factors: the density and the thickness of a given tissue and the absorption coefficient that is characteristic of that tissue. Low density material such as air is represented as a black structure, while a denser material like bone is represented as a white structure. (Hendee, William R.; Ritenour, 2002)

When dealing with images obtained by CT, these are intensity scaled (Hounsfield scale). The Hounsfield scale is a linear transformation of the attenuation coefficient of the radiation as it passes through matter. The radiodensity (amount of radiation detected) of distilled water, under standard pressure and temperature (STP), serves as a reference point for zero Hounsfield units (HU), while the radiodensity of air (minimum attenuation of X-rays) at STP is defined as the lowest point of the Hounsfield scale, with -1000 HU. (Cossio et al., 2012) This allows for ranges of Hounsfield Units to be linked to specific tissues. This not only allows for a clearer contrast between hard and soft tissue, but it also allows us to assign a range of intensities to a certain type of tissue/organs.

Figure 2. MRI image of the brain (Lda., MRI of Trinidad & Tobago, 2011)

MRI scanners use magnetic fields and radio waves to obtain information about the human body, as the patient is subjected to these, while inside the scanner to produce images. MRI takes advantage of protons (hydrogen atoms) that are present in the tissues in the form of water molecules. These water molecules then produce a signal that, once detected by the scanner, is subsequently used to acquire an image of the body. The different response of the tissues to this magnetic stimulation is determined and used to compute an image of the internal structures. The image acquired in a MRI scan depends on the initial parameters set for the acquisition of images. Since the results depend on these parameters and the characteristics of the patients body it is extremely difficult to obtain two identical images. (Cossio et al., 2012)

These images are stored in DICOM file format. It is the standard for manipulating, storing, and transmitting information in medical imaging. It stores cross sectional two-dimension data along with some patient's information (name, age, amongst other information).

Nowadays, the demand for sophisticated interactive exploration techniques is increasing, since the sizes of volumetric data sets are normally beyond what could be examined efficiently slice-by-slice. This heightens the need for 3D volumes. They consist of a set of 2D slice images acquired by CT or MRI. Normally, the 2D slices are obtained in a regular pattern and they have a regular number of image pixels.

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. The three-dimensional array can also be seen as a pile of two-dimensional arrays of data values and each of these two-dimensional arrays represents a slice, where each of the data values represents a pixel. 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)

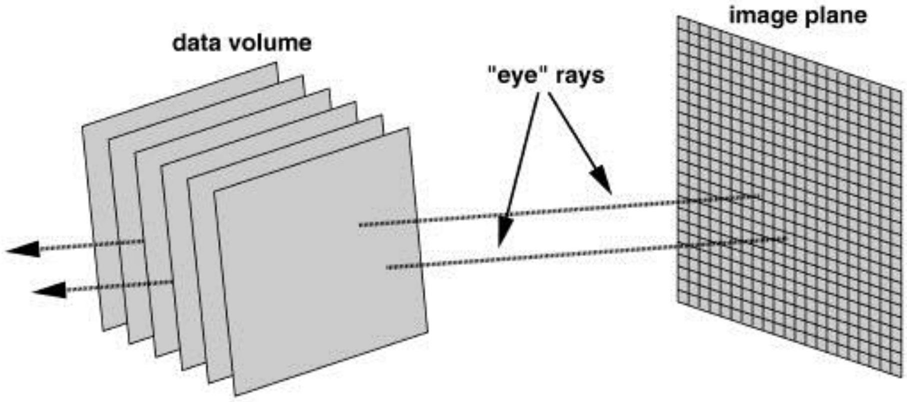

Figure 3. Ray Casting (Snavely et al., 1999)

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 (Figure 3). (Report and Zhou, 2003)

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, 2003)

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 an analogous process to the pseudo-coloring of black and white images obtained in CT. A key factor for the correct handling of these functions is to provide information about the domain that the user is currently working with. This lack of knowledge is limiting to obtaining the desired results. The unidimensional transfer function controls which voxels 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. Thus, transfer functions are maps that translate scalar information such as density, temperature, intensity into optical properties such as color or opacity. Since they are flexible and allow exploration of features from the underlying data they assume great significance in volume visualization.

Due to this flexibility, producing an optimized and meaningful transfer function becomes a significantly hard task. This fact motivates the study of transfer function design and the development of new interfaces for transfer function specification.

According to (Chandrajit, et al, 2006) there are some methods for designing transfer function and they are classified in four approaches:

- Trial and error: user has no information about the dataset, while they design the transfer function.
- Data-centric, without data model: The design of the transfer function is automatic, without making use of a data model.
- Data-centric, with data model: The design of the transfer function is semi-automatic since the user assumes a specific data model.
- Image centric: The user can interact with the volume rendering created with the transfer function.

The trial and error approach lets the user explore the design of the transfer function within its domain without any information about how it relates to the data, and thus is the less common approach. Data centric approaches are much more often used since they have a great trade-off between automation and user effort.

For data centric approaches that do not include an underlying model, 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.

Image centric approaches require little knowledge from the user, since the design of the transfer function is accompanied by changes in the rendered volume or the accompanying images, giving to the user immediate feedback on how the transfer function is related to the data in the volume.

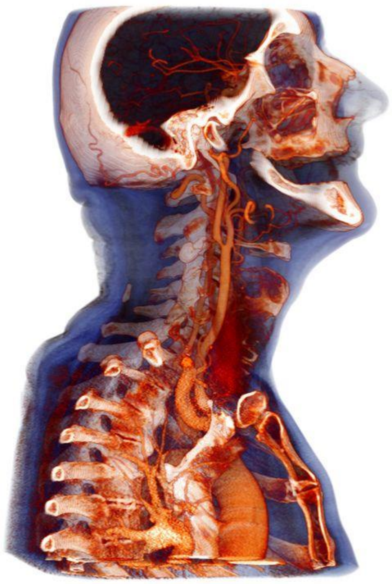

Figure 4 . Volume Rendering of the human body that can be used to study Medicine. (Medical School, 2015)

Volume rendering is often used for medical purposes like therapy planning scenarios, medical training or even educational purposes. The conventional approach of teaching Medicine has always relied on the study of anatomical structures represented in books and posters, which often requires the student to mentally build the appropriate context, a skill that is not always properly developed. Furthermore, the fact that the anatomical study based on manuals often leads us to a standardized presentation of a given structure, which means that structures of the body where a pathology is present, warping the structure, makes its recognition often more difficult by the physician. With this interface the relationship between structures is more explicit and develops a true representation of the anatomical structure and not the conventional one. This means that making a distinction between structures becomes an easier and more comprehensive task, which in the long run could lead to a better understanding of the information provided when compared to the standard printed manuals.

It is not enough to display and analyze the volume-rendered images. It is crucial to produce smart medical visualizations to yield apprehensible patient-related information, in which important anatomic structures are emphasized and a faithful representation of the area around the pathologies is achieved.

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.

The gradient consists of the contribution of the derivatives of a geometrical function in a scalar field. The gradient is denoted by ∇f (Equation 2.1), where **e1**, **e2** and **e3** consists of the orthogonal unit vectors pointing in the coordinate direction.

$$\nabla f = \frac{df}{dx}\boldsymbol{e1} + \frac{df}{dy}\boldsymbol{e2} + \frac{df}{dz}\boldsymbol{e3} \qquad (2.1)$$

Although a one dimensional transfer function is a user-friendly, robust tool with workable quality, and it does not involve any pre-computation, it has some major drawbacks, since it does not allow to discriminate features within a data set which have an overlapping intensity range of the data.

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.

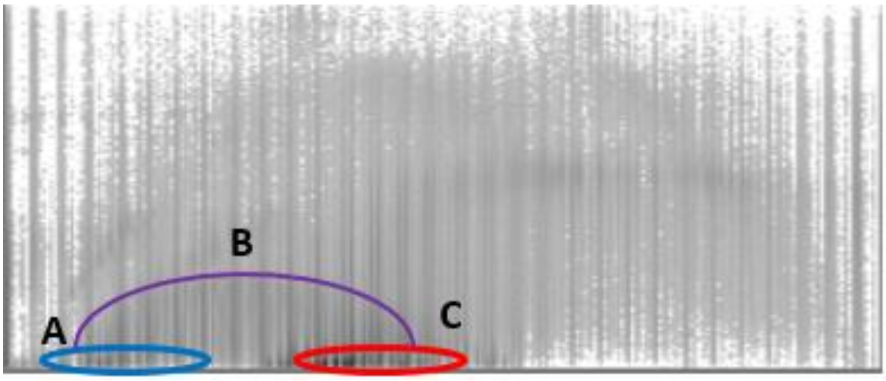

Figure 5.Typical arrangement of a 2D histogram. Tissues can be represented as circular regions (A and C) and the boundaries between these tissues can be represented as arc-like shapes (B).

Tissues that are relatively homogeneous present low gradient magnitudes. 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 (Figure 5). (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.

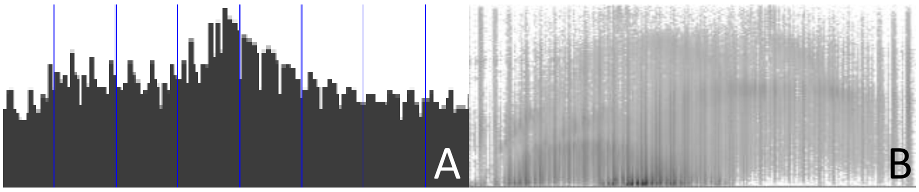

Figure 6. A. LH histogram B. 2D Histogram

Histograms may present the same information with different properties. While intensity-gradient histogram presents transitions between materials as arc-like shapes, LH (Low-High) histograms shows them as a region with high concentration of points. In the LH histogram, a value lies inside a material or in a boundary between two materials, and this does not differentiate between these two situations (Figure 6).

There is not a single transfer function that works for everything. The ideal transfer function depends on the dataset and the feature the user intends to explore, and it is up to the users expertise to determine the most suitable transfer function.

2.2 STATE OF THE ART

Volume rendering has allowed for the visualization of anatomical structures in great detail, becoming a more and more valuable tool for medical study, surgical planning, and other application within the medical context (Figure 7)

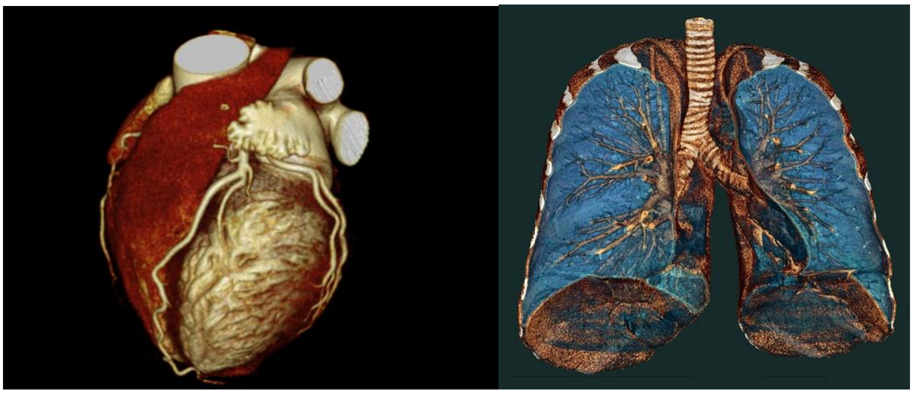

Figure 7. Volume Rendering anatomical structures. (Center, 2015), (Flickr, 2015)

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.

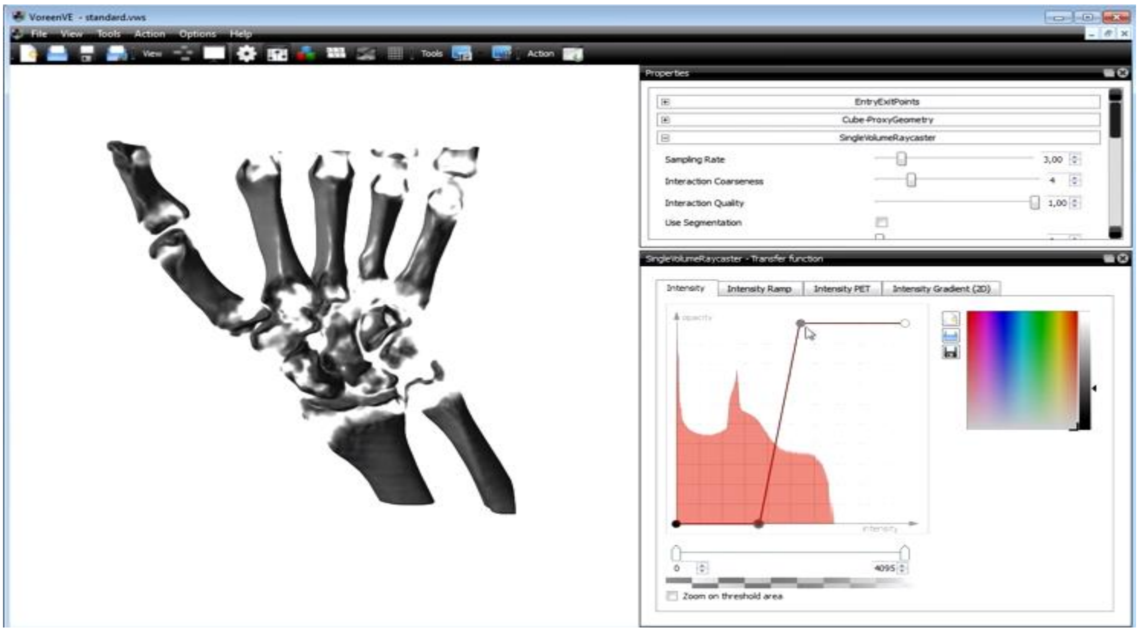

Figure 8 Voreen Interface

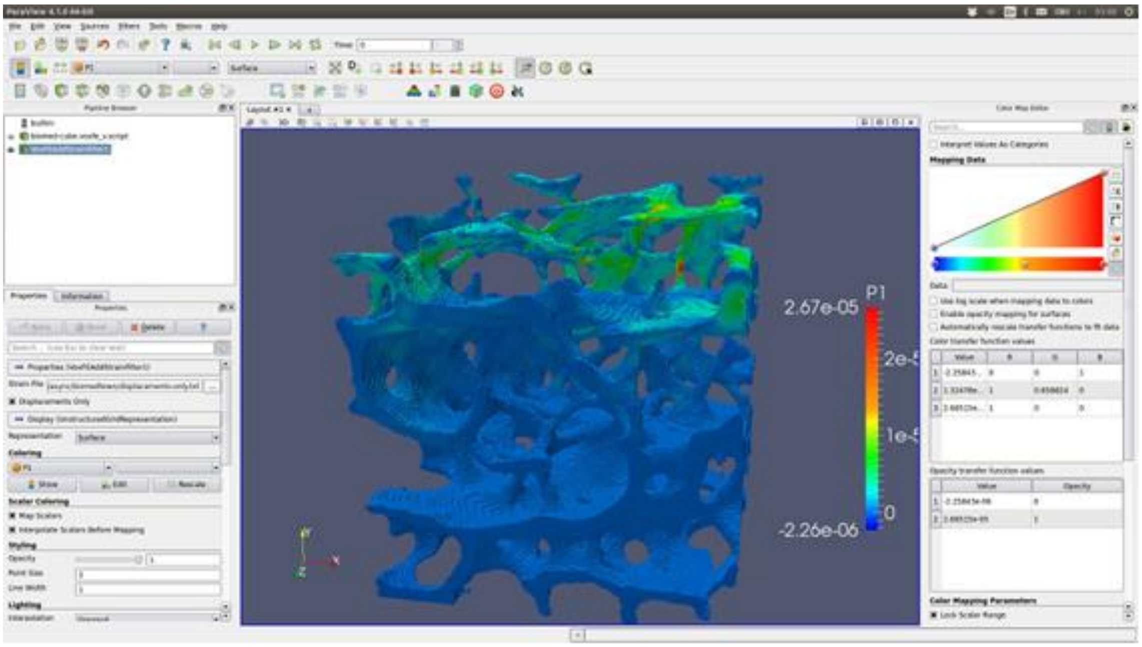

Figure 9 Paraview Interface

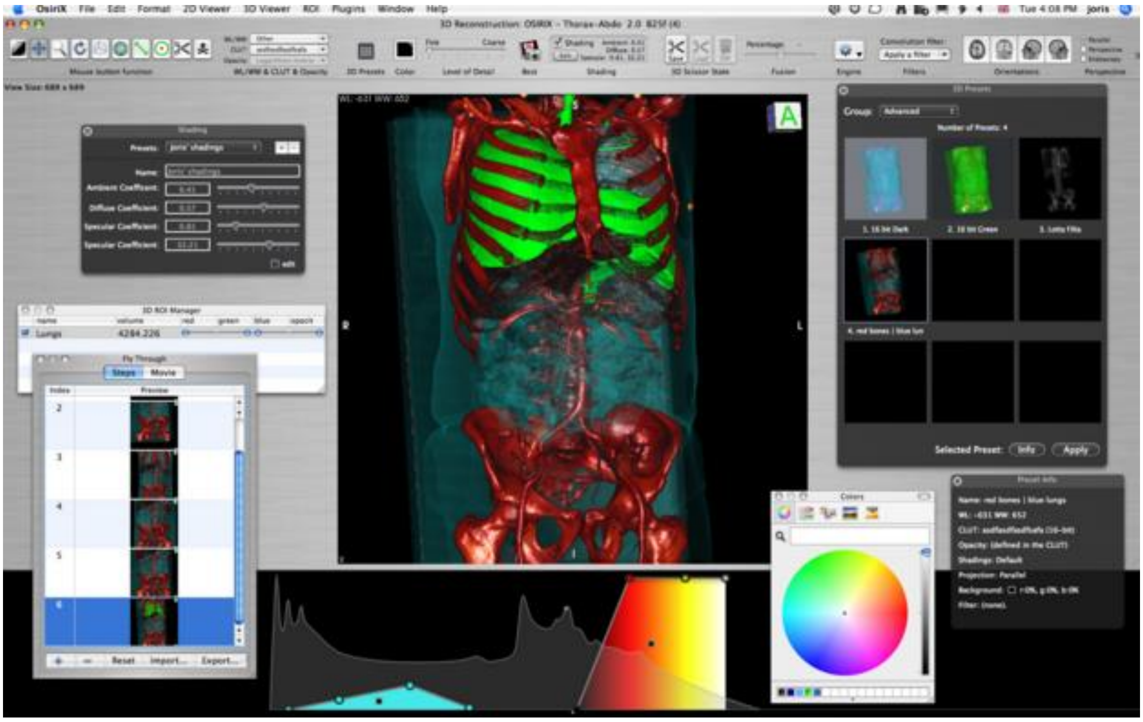

Figure 10. OsiriX Interface

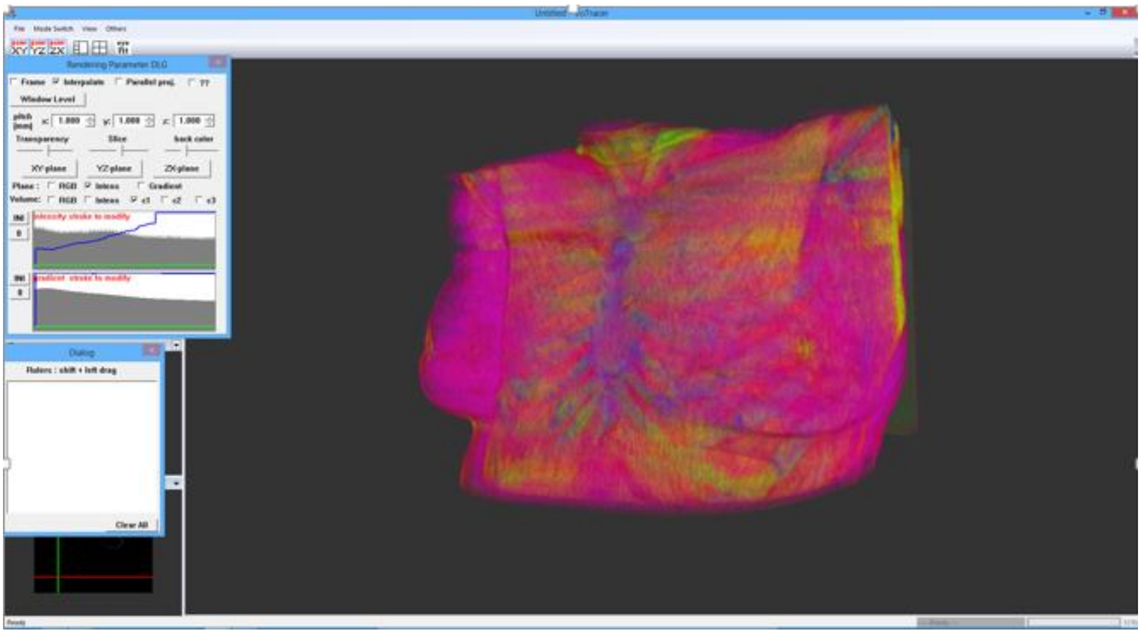

Figure 11. Votracer Interface

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 (Figures 8, 9 and 10). 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.

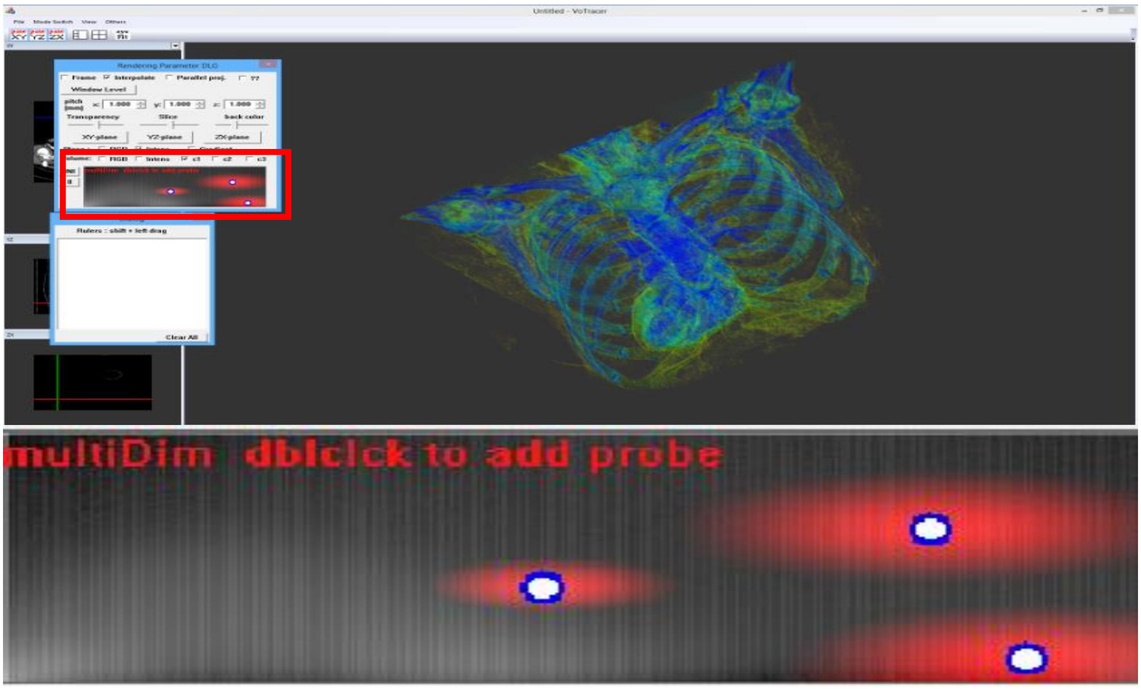

Figure 12 - Votracer 2D histogram

Some of these software also allow for the design of 2D transfer functions, where a 2D histogram is presented with information displayed with arc-like shapes for the boundaries and circular shapes for the different tissues. These software allow the users to freely select these areas in the transfer function domain, making use of polygons, and assigning color and opacity to each selection (Figure 12).

2.3 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 (where thre is no standard association between imaging intensity and tissue), it leads to a strong interaction based on trial and error by the user to define a new transfer function.

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.

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 such as dragging a step function left and right using the mouse.

This can became a major drawback for people who want to use transfer function design to study scientific data, and more specifically, physicians who wish to use these tools to better explore a patients anatomical structures either in a medical or educational context.

2.4 RELATED WORK

Several other research projects have looked into these problems and several possible solutions have been explored and documented, some of which this thesis is going to explore in this section.

Liu, Bingchen et al have explored an approach that aims to allow inexperienced users to acquire meaningful three-dimensional visualizations.

This approach takes advantage of the fact 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.

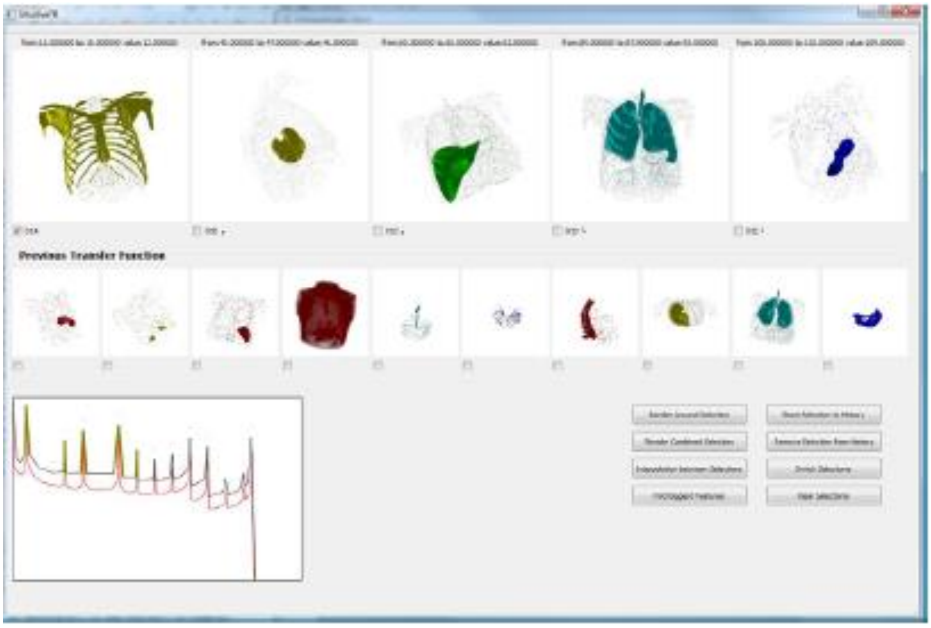

Figure 13. Unit Transfer Functions applied to each peak of the histogram. (Liu, Bingchen et al,2010)

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 (which increases linearly) are associated with that peak (Figure 13).

To make this possible a tool called Unit Transfer Functions was employed in order to create understandable and recognizable visualizations for the user, each visualization based on a different unit transfer function. 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.
Interpolation is applied to each two visualizations that are selected by the user, creating a "fusion" function, resulting in an interface that allows the user to combine, refine and change existing visualizations.

However, this approach has several problems. There are many tissues that do not correspond to histogram peaks, making their isolation a tricky task. The LH histogram itself requires complex computations (Šereda et al., 2006) and the user has no direct control of the transfer function it can result in, which can become a less accurate visualization when compared to traditional transfer function design. The lack of color control can be a problem as well, since dealing with materials colored with the same color can lead to ambiguities. Using only 1D transfer function associated with the restriction of identifying peaks in the histogram make this approach a less viable way to isolate structures in a data set. (Kniss et al.,2001)

Corcoran, Andrew et al approach allows the user to separate the most relevant structures from peripheral detail, which leads to an increasing understanding of the visual information along with spatial and anatomical orientation, using filtered analysis of the data set (Figure 14). In this approach the peripheral regions are not enhanced but they are conserved in a way that can provide spatial reference.

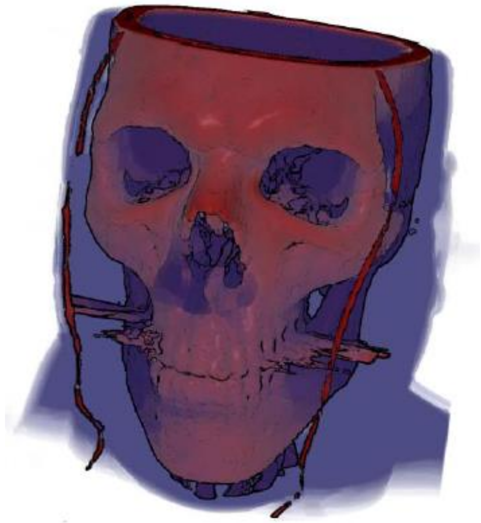

Figure 14. Representation of the skull obtained by (Corcoran et al., 2010) approach, taking advantage of Sobel Edge detection.(Corcoran et al., 2010)

Results of this study suggested that this approach is extremely useful in scientific illustration and for medical purposes, being able to improve the understanding of the volume data.

Although user understanding of the shape is increased while preserving context, which is especially effective for datasets which contain a large amount of peripheral volume data, the user can only deal with the internal structures and not with the boundaries which, is extremely limiting since many medical pathologies can lie within the boundary between different tissues.

Kindlmann et al promote the use of transfer functions based on curvature obtained by second-order derivatives. Different components of curvature information are used as domain variables in multi-dimensional transfer functions and in order to achieve an accurate curvature measurement a combination of filters for zero, first, and second derivatives were chosen (Figure 15).

In his research, curvature-based transfer functions were shown to extend the expressivity and the usefulness of volume rendering in several different contexts, highlighting differences between structures.

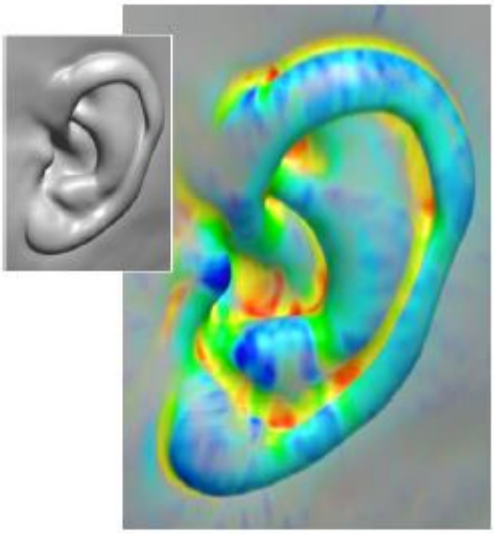

Figure 15. Curvature of the human ear obtained with Kindlmann et al approach.(Kindlmann et al., 2003)

On the other hand, there are some biological tissues like the skull that tend to be noisy. It means that when the surface curvature is low, like on top of the skull, it is not measured in an accurate way. Another major limitation relies on the use of piecewise polynomial filters which have a large number of parameters that need to be set correctly in order to obtain a reliable result. (Wilamowski et al., 2003) Because of these complexities and limitations, the resulting interface would not be very user friendly, limiting its application to environments where the user base has little knowledge regarding the application of filters.

In his work, Praßni, J. et all proposed a multidimensional transfer function that takes advantage of a structures shape to assign optical properties.

When exploring structures which are enhanced by contrast agents, sometimes it is not possible to discriminate between bone structures and vessels, since they share similar intensity values and gradient magnitude. Thus, the need for a new criteria to differentiate between these structures emerges.

Through the exploration of the curve-skeleton of each feature, a windowing pre-segmentation is performed, in order to perform shape recognition. Then, the algorithm for shape recognition classifies shapes in three categories: blobby shapes, surface-like and longitudinal shapes.

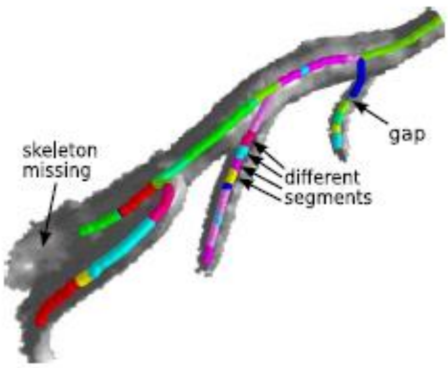

Figure 16. A non-normalized structure after the windowing pre-segmentation (Praßni et al., 2010)

After that, a skeleton normalization is performed, because there are some computation artifacts as well as some curve skeletons that cause some problems, followed by the fusion of skeleton regions into classifiable units (Figure 16). In order to assign optical properties to these classes of shapes, a traditional 1D transfer function is used.

However, this approach presents some problems, namely the inability to, most of the time, classify small structures, since they do not have a distinguishable shape, making this approach less reliable. Another limitation resides in the fact that the shape classification is time consuming, making it less desirable when an interactive interface is intended.

A data driven process approach can provide the user with information that may help them to gain knowledge about the volume data, which is the goal of Pekar et al in this work. When dealing with an isosurface display, the boundaries are the region of interest for the user to examine, instead of the areas that are formed by homogeneous material. These boundaries between materials typically consist of intensity transitions that are clearly dominant when compared to homogeneous areas which have small intensity variations. When dealing with CT datasets we can verify that transitions between soft tissue, fat and bone correspond to well-defined intensity transitions. (Drebin et al., 1988)

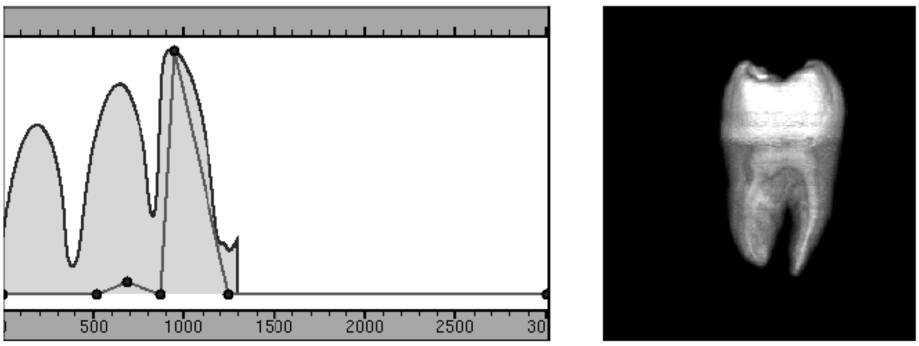

Figure 17. Opacity transfer function applied to the corresponding boundaries' isovalues.(Pekar et al., 2001b)

Taking advantage of these properties, the isosurface that represents the boundary of a certain area can be defined by this aspect, characterized by an intensity isovalue. In direct volume rendering, an opacity transfer function is applied to the corresponding boundaries' isovalues, reducing the opacity of the materials while enhancing the opacity of their bounding surfaces (Figure 17). (Levoy, 1988) This approach allows important intensity transitions to be highlighted easily and with potentially minimal user input.

Although computationally efficient, the use of this approach is restricted by the fact that tissue boundaries in MRI data often cannot be appropriately defined using global intensity isovalues, due to the variability of the image acquisition properties. Such feature makes this approach feasible only for images acquired by CT. (Jäger and Hornegger, 2009)

To properly select and explore isosurfaces, a tool needs to be designed so that it is able to properly select them regardless of the magnitude of the intensity transition or the nature of the medical images.

Exploration of the information present in a 2D histogram can be a difficult task and while tools such as the ones found in Votracer and in Voreen can help achieve the desired results, it is still difficult to correctly interpret the distribution of information.

To facilitate this process, Varshney and JaJa suggested that users can manually search for regions of interest through the inspection of different areas of a feature space. In this approach, Varshney and JaJa visually segment the intensity gradient 2D histogram of a volumetric dataset into an exploration hierarchy, making use of widgets to emphasize the intensity-gradient histogram so that the user can visualize the region of interest.

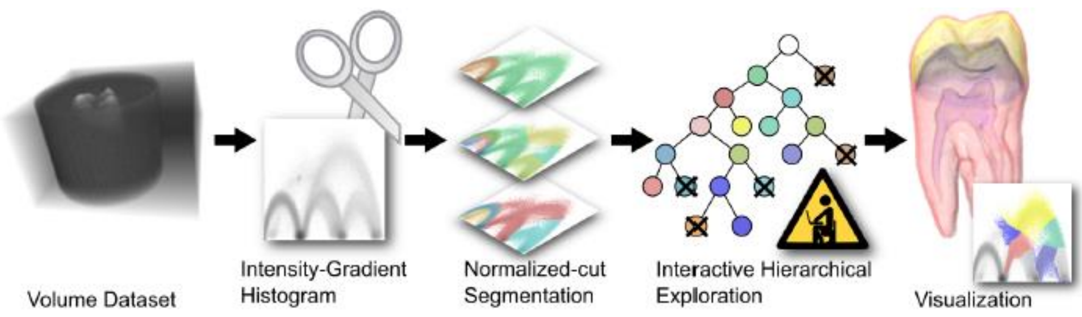

Figure 18. Workflow of the Hierarchical Exploration of Volumes Using Multilevel Segmentation of the Intensity-Gradient Histograms.(Varshney and JaJa, 2012)

To make this process less time-consuming, image-segmentation algorithms are used to cut along the shape of the histogram, which is segmented into several different parts in order to form a hierarchy to ensure an interactive exploration.

This hierarchy makes possible for users the exploration of the histogram segments from rough to fine details. Users interactively subdivide and explore selective regions of interest, and decide the subsequent exploration process, allowing the incorporation of users' knowledge in the exploration process.

Users can visualize the entropy or information gain using a color-coded visualization with an appropriate key press. The main goal is to allow the user to explore more informative segments, since entropy is used to characterize the complexity of a segment (Figure 18).

However, when the structure of interest is further subdivided the entropies of different components start converging and it becomes less clear which segment should be further explored.

In order to overcome this problem the information gain is computed. It is used to evaluate the effect of subdividing a segment and it consists in the reduction in entropy after a subdivision.

The main drawback is that this semiautomatic approach is based only on a 2D transfer function, and when applying it to data sets with a rather low signal-to-noise ratio, it is often hard to detect boundaries and differentiate the structures of interest. (Praßni et al., 2010) While the subdivision of areas allied to a color coding system is of great interest, the semi-automatic nature of this approach means that it may not always be reliable for all data sets and thus an approach with a more robust and customizable set of tools is preferred.

There are some situations where boundaries represent the features of interest, since the most relevant information resides there. Unfortunately, there are not many approaches that allow for a reliable boundary detection, since this process is characterized by some limitations like blurring. 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. Every voxel of the data resides either in a tissue or on a boundary between two tissues. To perform a LH histogram it is necessary to find the highest intensity between two tissues (FH) that forms a boundary as well the lowest intensity (FL) we can build an LH histogram and then accumulate voxels with the same [FL, FH].

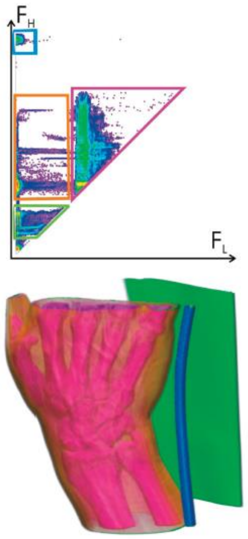

Figure 19. Visualization of Boundaries in Volumetric Data Sets Using LH Histograms(Šereda et al., 2006)

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 (Figure 19). In this approach, the gradient is used as a third dimension allowing the users to only deal with voxels that are located close to the edge, instead of dealing with all voxels that belongs to the boundary. Thus, only the voxels that are located on the edge are highlighted.

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. However, the major limitation of this approach is the slow computation times needed to obtain the desired results, which limits user interaction and customization.

Taking into account each approach presented in this section the goal is then to take advantage of the benefits highlighted by each one, improving upon of them when possible while avoiding some of the limitations that kept them from being considered ideal applications for volume rendering interfaces.

Table 1 –Summary of the previous approaches

Approach	Type of Approach	Benefits	Limitations
Unit Transfer Functions	Multiple 1D transfer function	Increase and take advantage of users domain knowledge	Not every tissue corresponds to a LH histogram peak
Boundaries as Spatial Reference	Filtered analysis of gradient function	Increased user understanding of the shape, while preserving context	Can only deal with the internal structures and not with the boundaries
Curvature-Based Transfer Functions	Second order derivatives of gradient function	Extend the expressivity and the usefulness of volume rendering in several different contexts	Difficult to obtain reliable results due to complex use of filters and noisy data
Shape Based Transfer function	Shape recognition and classification	Discrimination between structures that share similar values in terms of intensity and gradient magnitude	Small structures do not have distinguishable shapes, making this approach less reliable.
Semi-Automatic Detection of Isosurfaces	Assign optical properties to boundary isovalue	Allows important intensity transitions to be highlighted with potentially minimal user input	Tissue boundaries in MRI data often cannot be appropriately defined
Hierarchical Exploration of Volumes	2D Transfer Function defining regions of interest	Exploration of the histogram segments from rough to fine details, with color coding	Based only on a 2D transfer function. Hard to detect boundaries and differentiate the structures of interest in low signal-to-noise ratio data sets
Visualization of boundaries through LH Histograms	Selection of 2D areas of interest in LH histogram	Selects boundaries that would otherwise be difficult to isolate using 2D histograms	Slow computation times, limits user interaction and customization.

CHAPTER III

3 METODOLOGY

One way to overcome the limitations explored in Chapter II, especially in terms of function design and data exploration, consists in drawing directly the transfer function and increase the feedback on the represented volume for the user, providing a combination of spatial information to spatially independent information of the transfer function.

The use of sketches and multi touch gestures for designing transfer functions on an interactive surface is an area that has not been properly explored.

As referred in motivation, 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. Once the data is explored and the structures of interests are identified, users could easily draw their transfer function, but this time not only with a decreased attempts-error number, but also in a smaller range of time. This interface relies on high user interactivity, enabling a better user experience as well as promoting greater engagement, since that the user is an active participant in the sketching of the final transfer function. This addresses one of the major limitation present in the work explored in chapter II. By promoting an increased involvement by the user we hope to produce a better understanding of the information constrained in the domain of the transfer function. It allows us to address one of the major constraints experienced in the transfer function design: the user's lack of knowledge about the transfer function domain. (Pinto and Freitas, 2008a)

3.1 VOXEL TIPS

3.1.1 TRIDIMENSIONAL REPRESENTATIONS

The representation of volumes is based on a set of techniques used to display a 2D projection of a set of voxels that are defined as a scalar field. For that purpose we used 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 (Figure 20). (Zimmermann et al., 2000) (Cullip and Neumann, 1993)

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. Due to the fact that only one texture is allowed to be displayed without creating performance problems, a particle-based volume rendering with a lower resolution was used in order to represent the voxels in certain intensity ranges. Several approaches have used particle systems to represent volumes of interest.(van Pelt et al., 2008) However, since these particle systems require the use of CPU, and due to the number of systems used, the resolution used for these systems had to be reduced.

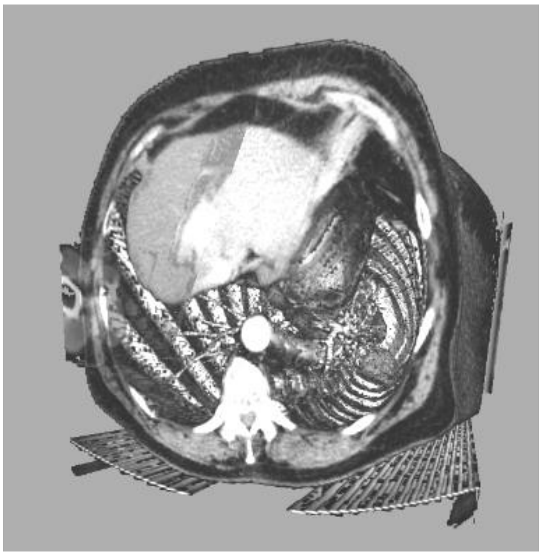

Figure 20. Tridimensional volume displayed in Voxel Tips

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 21) These controls resemble the types of controls usually employed in touch devices, such as cellphones. To turn the volume along a vertical axis, the axis is defined by the first contact finger with a second finger determining the rotation direction.

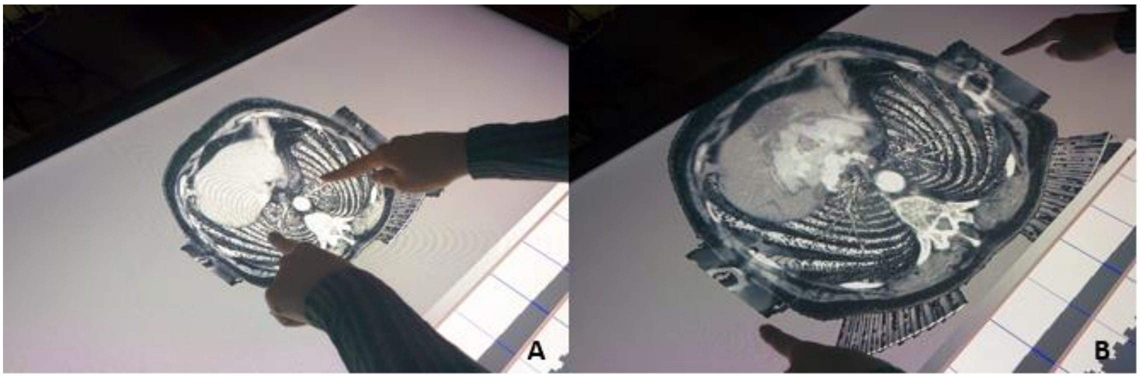

Figure 21. Moving the fingers towards each other the user is able to zoom out (A) and away from each other is able to zoom in (B)

All gestures that control a given action resemble metaphors based on computer desktop and/ or windows or even daily situations so that the user can easily and quickly apprehend the gestures that control an action. (Isenberg and Hancock, 2012)

If the user touches the surface with the five fingers of the hand, the volume will follow the hand position, allowing the user to drag it to any point of the working space. The user can also return it to its initial position and rotation with three consecutive touches on the touch surface. This was inspired by the knocking motion that one usually uses when summoning someone at the door. Volume manipulation is limited to touches above 40 % of the screen height. This was done in order to avoid accidental/unwanted interaction with the volume while using the remaining functionalities.

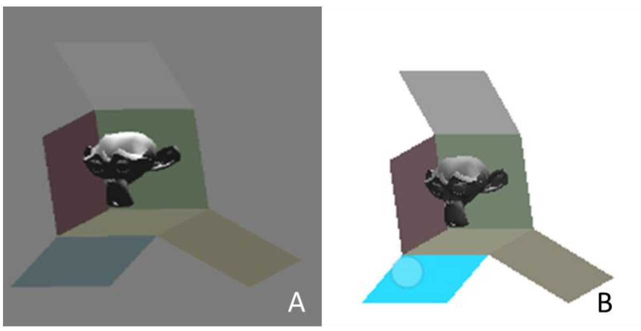

Figure 22. **A**.Open box in Voxel Tips **B.** Open box when one of its cube faces is selected

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 (Figure 22). For example, by selecting the lower face of the cube, the underside of the volume would be displayed.

3.1.3 Transfer Functions

The transfer function consists of an explicit mapping of input values, which are subsequently converted into an output point. In the case of volumetric data, each voxel is examined and an input value is obtained, as well as the corresponding output value and optical properties, which would be applied to the same voxel. The corresponding output value is determined by the transfer functions applied to the volume data.

These can be classified as one-dimensional (only accepts an input parameter) or two-dimensional (accepts two). They can also be classified as spatial (in case the input values is a spatial variable) or non-spatial. Typically, 2D functions are spatial and the second input variable is a spatial coordinate, such as curvature information or second partial derivative of voxel intensities.

Most software present, by default, the three-dimensional image in gray tones or with a predefined color mapping. Thus, the transfer functions are used in order to assign optical properties, namely color and opacity to these volumes.

When dealing with 1D functions, that is, for every possible value of a single input (being this set of values referred to as the function domain) there is a direct mapping to an output value without the need of added mathematical operations. 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.

This approach allows Voxel Tips 2D to be a more versatile and customizable tool, offering a better sense to users of how the data is distributed through the domain, in contrast to what is offered by conventional software.

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 as a 1 and the corresponding voxels are granted full opacity, while points outside the selection are defined as 0, with full transparency of the voxel.

3.1.4 PLATAFORM OF FUNCTION DESIGN

The main purpose of this thesis is to explore new ways to design transfer functions for 3D representations generated with medical images using a sketch-based interface.

The user interface consists of a table of large dimensions, which allows greater freedom of movement, with which the users interact using gestures that can be detected and identified. The table itself consists of a large-scale television, arranged horizontally, where the users can perform the visualization of data. There is a multi-touch sensor system installed over the boundaries of 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 (Figure 23).

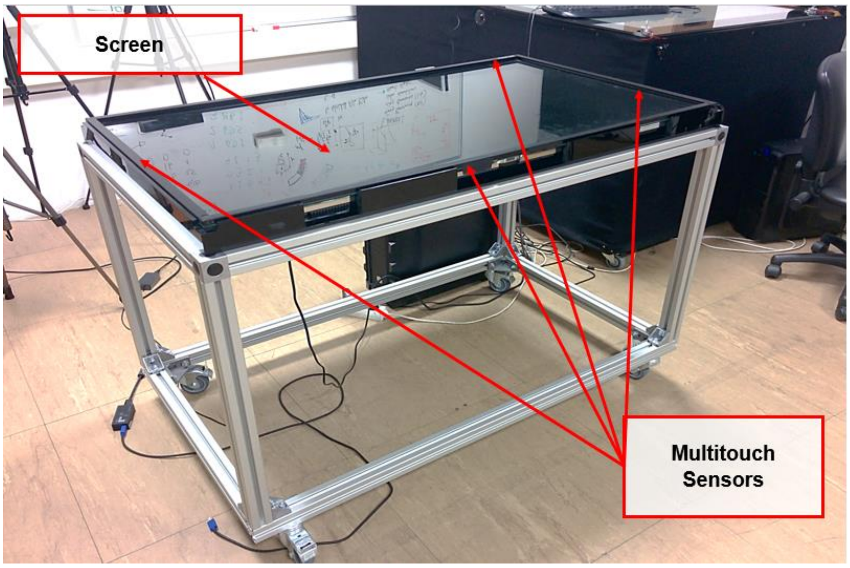

Figure 23 . Table and multitouch sensors.

The main application itself consists of the medical imaging volume in the top center of the screen, and the lower area is devoted to drawing tools.

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.

The main application was developed using the Unity3D engine and run with Windows 7 operating system. Unity 3D is a game engine platform developed by Unity Technologies. It is used in the development of video games for PC, consoles, mobile devices and websites

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. Applications like Volview, Voreen, etc are much more difficult to develop for because of limited and often poorly documented libraries and the lack of available development tools and experience.

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3.1.5 TRANSFER FUNCTION DESIGN

The purpose of these functions is to demonstrate specific tissues or anatomical structures within the imaging volume acquired by CT or MRI, although the process of trial and error involved in obtaining these results turns out to be too burdensome in traditional software. To mitigate these limitations a number of features are proposed with the main goal of decreasing the process of trial and error, giving the user ways to explore the data volume faster and in a more natural and informative way. The fact that this interface can isolate structures of interest, whether its volumes have been acquired by MRI or CT mitigates one of the main gaps presented in Chapter II. (Pekar et al., 2001)

These features are 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.

As discussed in Chapter 2, the transfer function design can be separated into several categories. In the case of the presented interface, we can classify it as an image centric transfer function design approach.

The following tools aim to solve the problems addressed in chapter II, namely involving the user in the transfer function design, making 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 is not based on histogram peaks alone but instead of that it relies on the user's domain inspection.

3.1.6 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. (Pinto and Freitas, 2008) The main purpose for this feature is to be used to aid in the transfer function design. Each thumbnail shows the voxels represented by range of values from the domain, directly above. Thus, 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 (Figure 24). This feature also serves to compensate for 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, in particular the intensity of the voxels and the volume structures.

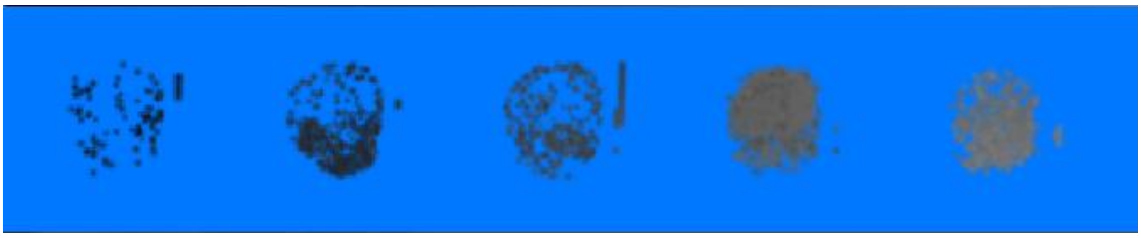


Figure 24 Thumbnails

3.1.7 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 (Figure 25). This function was create as an equivalent to the standard transfer function design present in several traditional software. Due to practical reasons concerning user tests, it was not as heavily explored in this thesis.

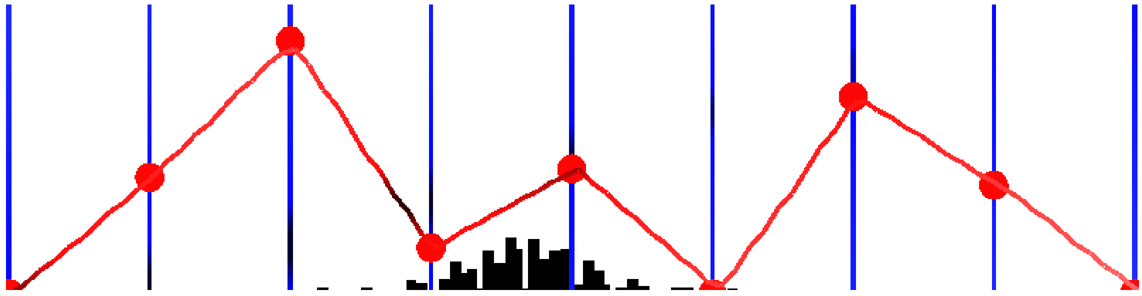


Figure 25. Ramp-like function

3.1.8 SLIDING WINDOW

As a way to solve the lack of user knowledge about the transfer function domain this tool was proposed. 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 (Figure 26). 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. The window can be dragged through the domain allowing for the full scan of the data with an interval resolution defined by the length of the used window.

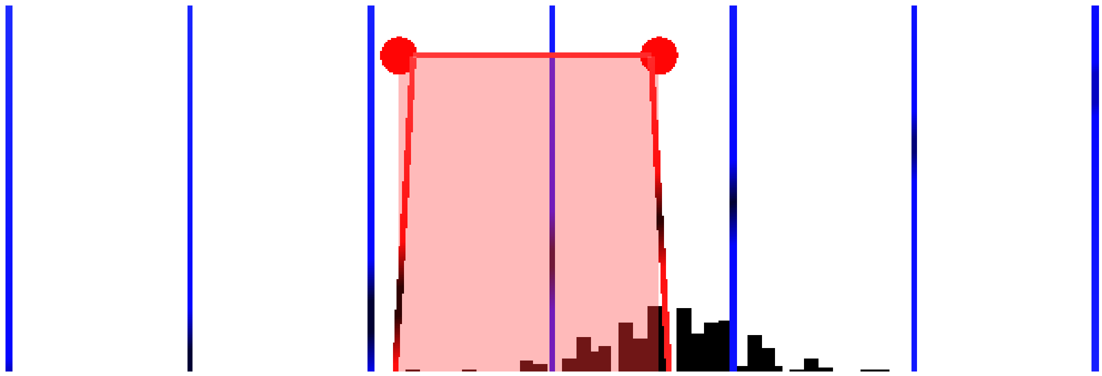


Figure 26. Sliding Window

3.1.9 MULTIPLE SLIDERS

The screen is divided into ten segments. Each segment 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 (Figure 27). Several sliders can be moved simultaneously, exploring the metaphor of a DJ mixing table. The 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 (maximum). This feature allows the user to select areas of interest more quickly and thus obtain a faster approximation of the desired transfer function.

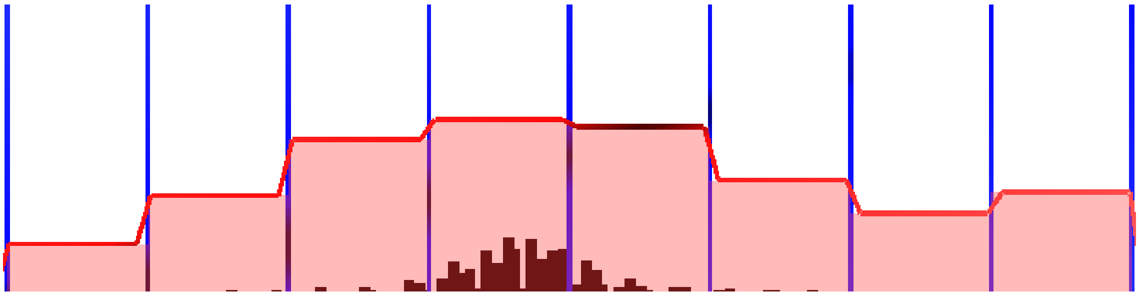


Figure 27. Multiple Sliders

3.1.10 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. This allows the user to make more precise changes in the transfer function without the need to redesign the function in its entirety (Figure 28).

Such functionality allows for a greater involvement by the user, and requires an understanding of the location of the data of interest. This knowledge has been built by using the proposed sequence of tools: Sliding window, Multiple Sliders and Sketching. Thus, it confers a better understanding of the data by the user, which in turn reduces the trial-and-error associated with the design of the desired transfer function.

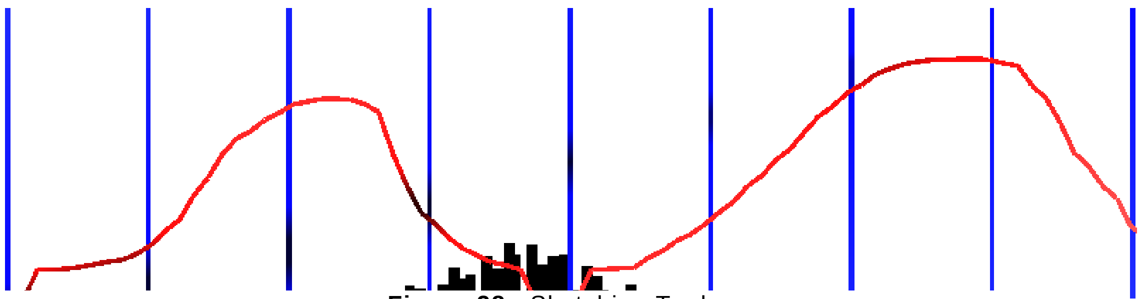


Figure 28. Sketching Tool

3.1.11 COLOR ASSIGNMENT

When the analysis of 3D medical images is made, the color assignment is an important tool. This is what allows the distinction of similar tissues (associated with similar but distinct domain values) when they have the same opacities or when they are indistinguishable to the user.

In this thesis an allocation of simple colors is proposed. It is performed with a minimum presence of the screen and takes advantage of the interaction with gestures.

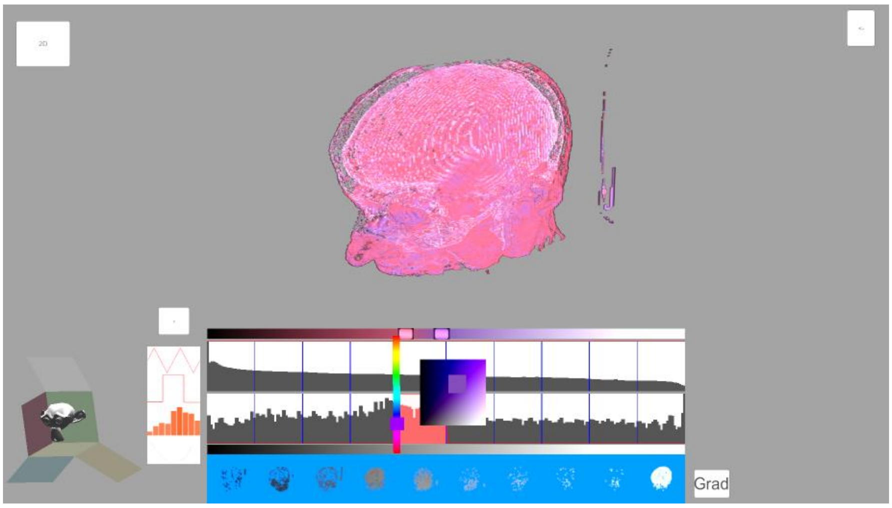


Figure 29. 1D Color Assignment

To achieve this two grayscale bars positioned directly above and below the white screens were used. 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, which consists of a color bar and a square that displays the different saturation and luminosity of the color (Figure 29). The selected color is applied to the cursor in real time and the color is assigned to the volume. This method was chosen because it is a simpler way to assign color, due to the inherent simplicity of the process. (Kniss et al., 2010) The position of the cursor on the bar will indicate the domain value that the color is applied to, and then interpolated up to the bar limits or to other assigned colors, if other cursors are present. The elimination of colors is done by dragging the cursors outside the bar and dropping them. If the cursor is dropped elsewhere on the bar, it will change the cursor position.

If dropped into the screen, two cursors will be created and placed in the range limits, where the cursor was dropped. Thus, this intensity range presents the solid color assigned to the cursors.

The bottom gray scale bar is used solely as a reference to the original colors of the volume data and are not interacted with.

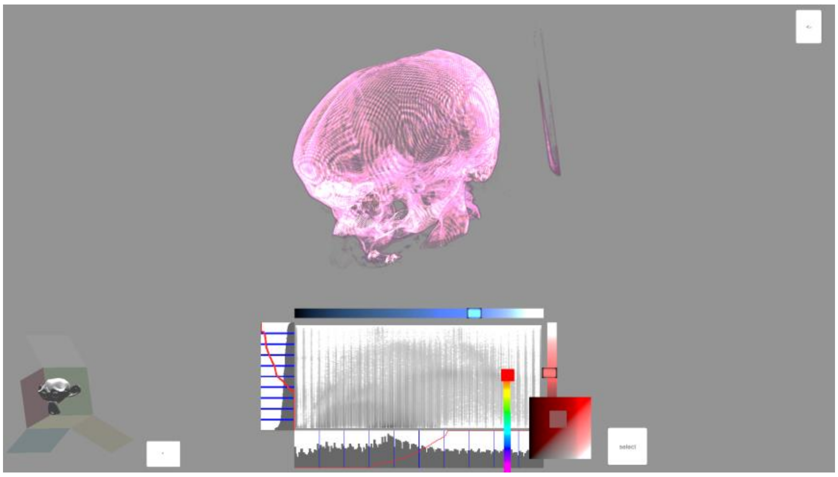


Figure 30. 2D Color Assignment

Assigning colors with the 2D histogram is similar to the 1D case, but the second gray scale bar can now be interacted with and displayed in the vertical position. (Figure 30) When colors are assigned to the vertical bar these are mapped to a specific value of the gradient data in a similar fashion to the assignment colors to intensity values. The two color vectors are then used to create a color matrix that assigns a specific color to each voxel with a discrete value of intensity and gradient. The color assigned to each value of the matrix is defined as an interpolation between the colors of the corresponding intensity and gradient values.

This results in a more visually appealing volume, as well as providing a more versatile and robust color assignment.

3.1.12 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, even though they have the same intensity value. (Šereda and Gerritsen, 2006) In order to map the gradient magnitude to opacity, the same architecture used in 3.1.5 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. (Ca. Aravid, 2015) The 3D Sobel operator performs a 3D spatial gradient measurement where a 3x3x3 kernel is used to compute each of the partial derivatives. The kernels used for x, y and z directions are represented below:

For x direction (x-1, x and x+1, respectively):

$$\begin{pmatrix} -1 & -3 & -1 \\ -3 & -6 & -3 \\ -1 & -3 & -1 \end{pmatrix} \quad \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} \quad \begin{pmatrix} 1 & 3 & 1 \\ 3 & 6 & 3 \\ 1 & 3 & 1 \end{pmatrix}$$

For the y direction (y-1, y, y+1, respectively):

$$\begin{pmatrix} 1 & 3 & 1 \\ 0 & 0 & 0 \\ -1 & -3 & -1 \end{pmatrix} \quad \begin{pmatrix} 3 & 6 & 3 \\ 0 & 0 & 0 \\ 3 & 6 & 3 \end{pmatrix} \quad \begin{pmatrix} 1 & 3 & 1 \\ 0 & 0 & 0 \\ -1 & -3 & -1 \end{pmatrix}$$

For the z direction (z-1, z, z+1, respectively):

$$\begin{pmatrix} -1 & 0 & 1 \\ -3 & 0 & 3 \\ -1 & 0 & 1 \end{pmatrix} \qquad \begin{pmatrix} -3 & 0 & 3 \\ -6 & 0 & 6 \\ -3 & 0 & 3 \end{pmatrix} \qquad \begin{pmatrix} -1 & 0 & 1 \\ -3 & 0 & 3 \\ -1 & 0 & 1 \end{pmatrix}$$

Regions with high spatial frequency are emphasized as these regions correspond to boundaries and is essential to perform edge detection for object recognition of human organs. (Singh, 2014) Different kernels are applied separately to the input data in order to obtain the gradient component in each direction of the reference axis. Once computed, these components can be used to determine the magnitude of the gradient, given by the square root of the sum of squared magnitude of the gradient in x (Gx), y (Gy) and z (Gz) (Equation 3.1)

$$|\nabla f| = \sqrt{Gx^2 + Gy^2 + Gz^2} \qquad (3.1)$$

Gradient magnitude allows for the distinction between homogeneous regions and transition regions and it is of great value in a medical context, since the feature of interest is often between two tissues.

The manipulation of the gradient overcomes one of the limitations referred in chapter II, (Corcoran et al., 2010), in which the user cannot manipulate boundaries.

3.1.13 Usage of the Transfer Function

The features of the single window, ramp-like function and the multiple sliders allow for an approximation of the transfer function. However, these features do not allow refinement of the function, and this step has to be carried out by the sketching tool that allows greater control of the function design.

When the user exchanges between functionalities, the prior transfer function is adapted to the new tool, retaining part of its information. The lost information is associated to the different ways that these tools affect the transfer function. For example, switching to the sketching tool leaves the transfer function unchanged, while switching to the multiple sliders, positions them according to the average of the values in the range of each slider.

By manipulating volumes with transfer functions, loss of information complicates the analysis of the data, increasing the time required to achieve the desired results, which is of course against the purpose of this thesis. Thus, 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 31. This selection of tools can be applied independently to the intensity and gradient transfer function.

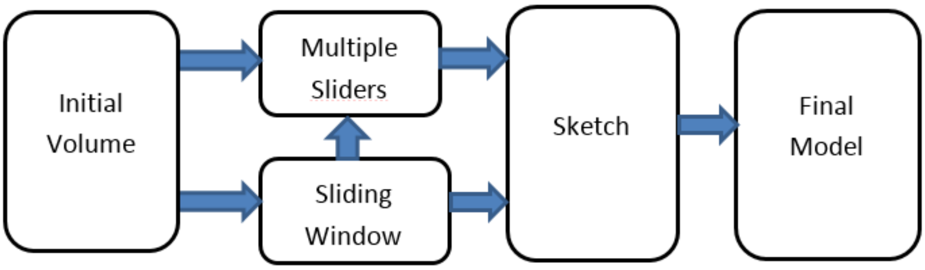


Figure 31. Sequential set of tools proposed to design the intensity and gradient transfer function.

3.1.13 2D HISTOGRAM

A screen is used to display a 2D histogram. As referred to chapter II the histogram has a typical way to represent materials and boundaries, which are represented as circular spots and arc-like forms, respectively. 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. Thus, the user can have a better understanding of the 2D histogram and of the area they need to select, something that other approaches do not allow. Since the volume consists of a balance between the gradient contribution and intensity, the volume becomes visually more appealing and with a great degree of detail. There is also a color assignment to the gradient contribution, which was discussed in section 3.1.11. 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. This algorithm evaluates how often a ray originated at a given point and in a given direction crosses the boundary of the shape. If the point is within the polygon selection, it will cross the border an odd number of times and if it crosses an even number of times, the point is found out outside of the polygon (Figure 32).

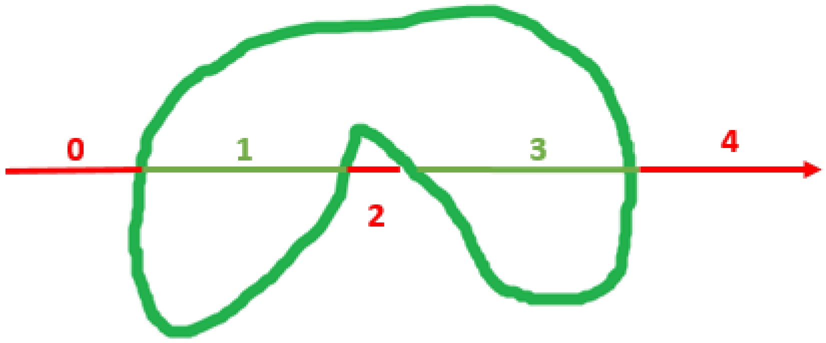


Figure 32. Jordan Curve Theorem. If the point is within the polygon selection, it will cross the border an odd number of times and if it crosses an even number of times, the point is found out outside of the polygon.

The user can switch between the features of selection and deletion of a region, through a lateral button created to switch between these two forms of selection. Both options work in an identical manner, so to distinguish between the two options a selection is done with a green line while deletion is done with a yellow line.

CHAPTER IV

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.

All images used for constructing volumes were acquired by Computer Tomography. The images used were obtained from a brain tumor and lung carcinoma, known as tests 2 and 3 respectively. These images were obtained through the OsiriX image database, referred to as BRAINIX and CARCINOMIX respectively. Test 1 was referred as PELVIX in the same database (Figure 33).

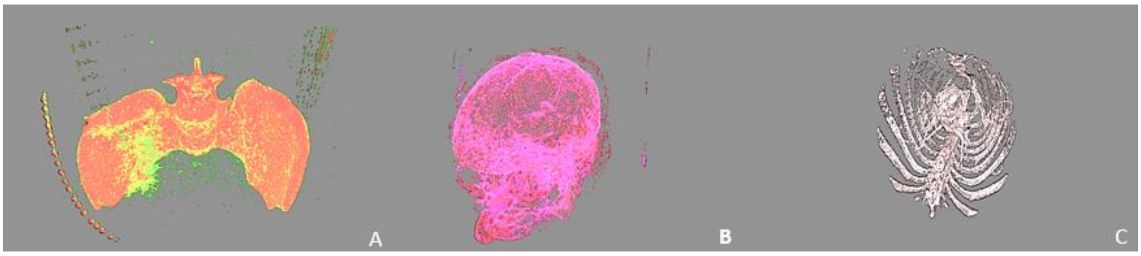


Figure 33. User Tests volumes. A. Pelvix B.Brainix C.Carcinomix

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. Each user began each task with one attempt and a new attempt was considered every time the user performed one of these actions:

- The user reset the function to its original state;
- The user reverted the function to a previous form;
- The user designed the function that was not intended;

While the order of the tests were similar in both interfaces, some notable differences were present, which will be discussed below.

When dealing with Votracer the user had to mimic the image acquired previously, manipulating the intensity and then gradient, through a WIMP approach. This was done by using the mouse pointer to draw a function over the canvas (Figure 34). Finally, the user tries to obtain the desired results using a 2D histogram, where the selection of the areas of interest is done by instantiating objects that select an elliptical region around its center. These objects can be translated through all of the domain of the 2D histogram.

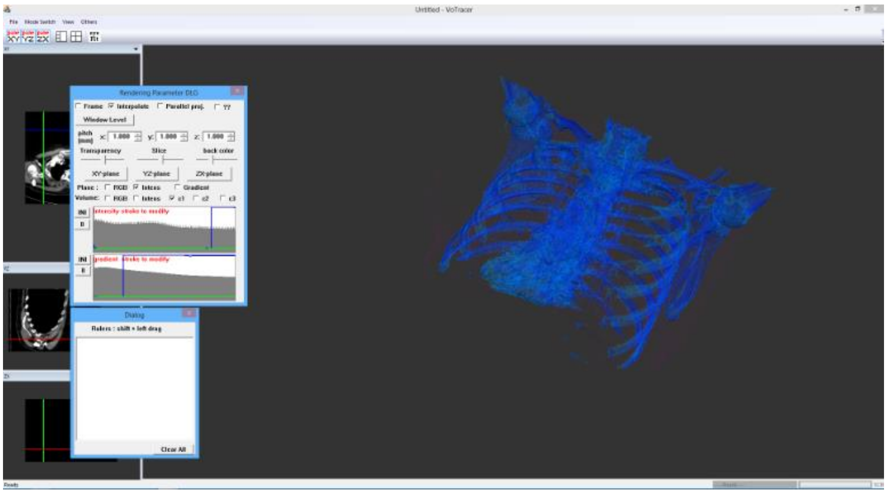


Figure 34. Votracer user interface with intensity and gradient transfer functions

When using Voxel Tips the user had to perform similar tasks, starting with the design of the intensity transfer function. The user performs the scanning of all the domain with a single window that permits to inspect the location of the voxels of interest. As soon as the user has completed this step, the sliding windows are selected so that the user can assign a non zero opacity to the region of interest. Finally, the user has the chance to manually sketch the transfer function.

The user is then asked to assign colors to the volume to match the image presented of the desired result. This task was not timed due to the lack of similar color selection in Votracer, and thus a lack of a control group.

The user was then asked to obtain the desired results using exclusively the tools provided for the design of the gradient function, in a similar fashion to the design of the intensity transfer function.

When this task was finished, the user had to draw the same gradient function, but using only the sketch function with the presence of the 2D histogram. This step was added to determine if the users were able to retain the knowledge previously acquired during the transfer function design.

In order to select the region of interest in 2D histogram, the gradient and intensity functions are set to maximum opacity. The user is then asked to obtain the desired result using solely the 2D histogram.

After all tests were completed, the user was asked to fill out three questionnaires about their experience.

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.

CHAPTER V

5 RESULTS

5.1 USERS

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

5.2 Analysis of the Survey Results

In order to evaluate user experience, most multiple choice answers were presented in a scale between 1 and 4, where 1 represents the most negative answer and 4 represents the most positive answer.

When asked by the difficulty felt when using the tools presented by Voxel Tips, most of the users considered the sliding window and the multiple sliders to be easy to use (m=3,63, sd=0,64; m=3,73, sd=0,46, respectively), and they were considered to be effective for obtaining results. (m=3,47, sd=0,64; m=3,93, sd=0,26, respectively).

When asked about their preferred tool, users were mostly divided between both tools, with sliding window being preferred by (53 %) of the users.

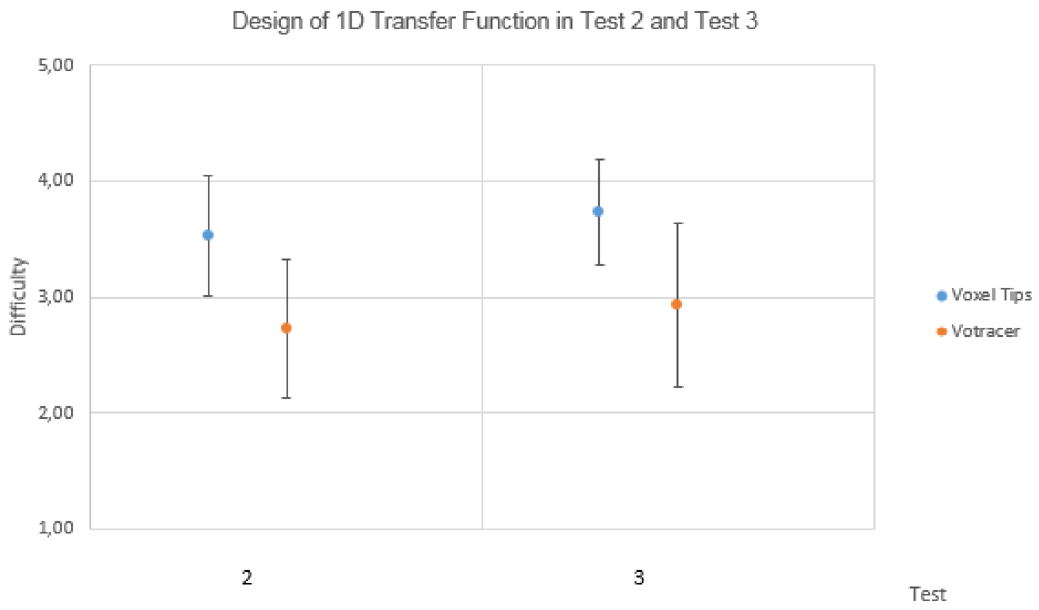


Figure 35 Difficulty in the design of 1D transfer function in Test 2 and Test 3

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) (Figure 35).

Along with these results, users found the sketching tool to be easy to use in Voxel Tips. (m=3,40,sd=0,51).

The users considered that Voxel Tips confers an increased comprehension/knowledge of the relationship between the intensity domain and the volume acquired by their selection, when compared to Votracer (m=3,80, sd=0,41; m=3,00, sd=0,65, respectively).

When dealing with the gradient, the users considered that Voxel Tips offers a better and easier method to determine the initial approximation of the transfer function in both tests 2 and 3 (m=3,20;

sd=0,68, m=3,67, sd=0,49, respectively), when compared to Votracer (m=2,80,sd=0,77; m=2,53; sd=0,64, respectively). All users also found that the set of tools proposed in this thesis is very useful to aid in the gradient transfer function design, but when asked to make a choice about their preferred tool to deal with the gradient, the users chose the sliding window (60%). It was also shown that in Voxel Tips the relationship between the gradient domain and the acquired volume is clearer (m=3,33, sd=0,49) when compared with Votracer (m=2,73, sd=0,59).

When dealing with the 2D histogram the users considered that selecting areas in the 2D histogram in both tests was easier in Voxel Tips (m=3,60, sd=0,51; m=3,47; sd=0,74), when compared to Votracer (m= 2,67, sd= 0,98; m=2,87; sd=1,13). The users also considered that, in Voxel Tips, the 2D histogram confers an increased comprehension about the relationship between the domain and the acquired volume (m= 3,47, sd=0,52), when compared to Votracer (m=2,93, sd=0,80).

However, in Voxel Tips, when users are dealing with the gradient transfer function they prefer to obtain the desired function with the subset of tools proposed in this thesis (53%), not with 2D histogram (47%). They also considered that this subset of tools provided a better data comprehension in both tests (60% for both tests 2 and 3).

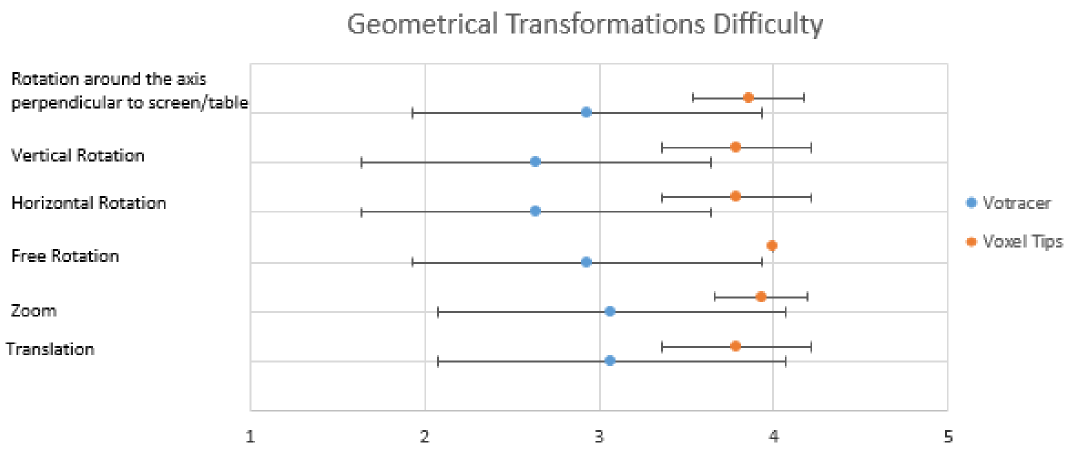


Figure 36. Difficulty felt by users to perform Geometrical Transformations in both interfaces: Voxel Tips and Votracer.

When surveyed about the geometrical transformations on the volume, the users almost unanimously considered that performing a geometrical transformation was easier on Voxel Tips for every type of interaction (Figure 36).

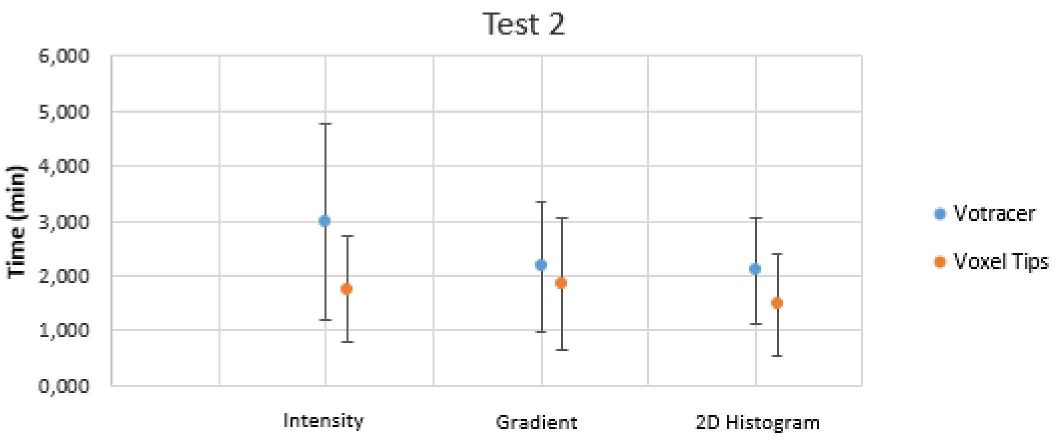
When inquired about the way that the open box, in Voxel Tips, helped in the manipulation and the exploration of the volume, the users found it useful (m=3,13,sd=0,83) . The thumbnails were also considered useful in the transfer function design by users (m=3,33; sd=0,98).

Most users found that the Voxel Tips reset command was easy to use (93%) and that the interface has an adequate number of buttons (100%) and a coherent layout (m=3,60,sd=0,51). They also considered that identifying the buttons purpose was easier in Voxel Tips, when compared to Votracer (m=3,40; sd=0,63).

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%).

Users mostly prefer the use of touch controls for the design of 1D transfer functions (87%), gradient function (93%) and for the manipulation of volumes (100%) which further supports their preference for Voxel Tips.

5.3 User Test Results



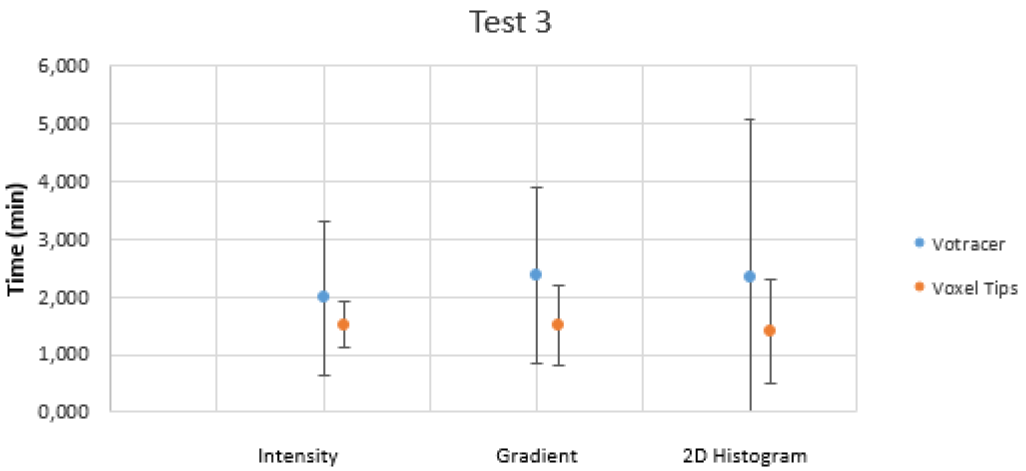
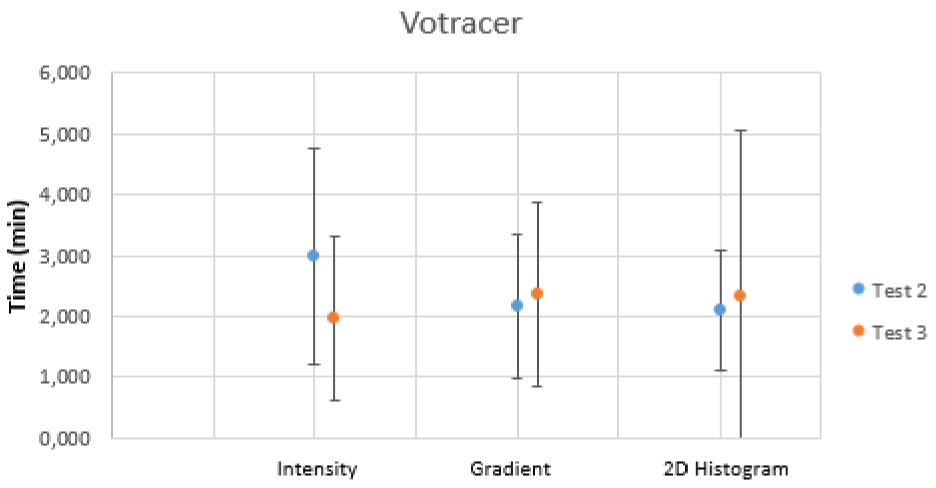


Figure 37. Users performance in both interfaces in test 2 and test 3, respectively.

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.

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 37).



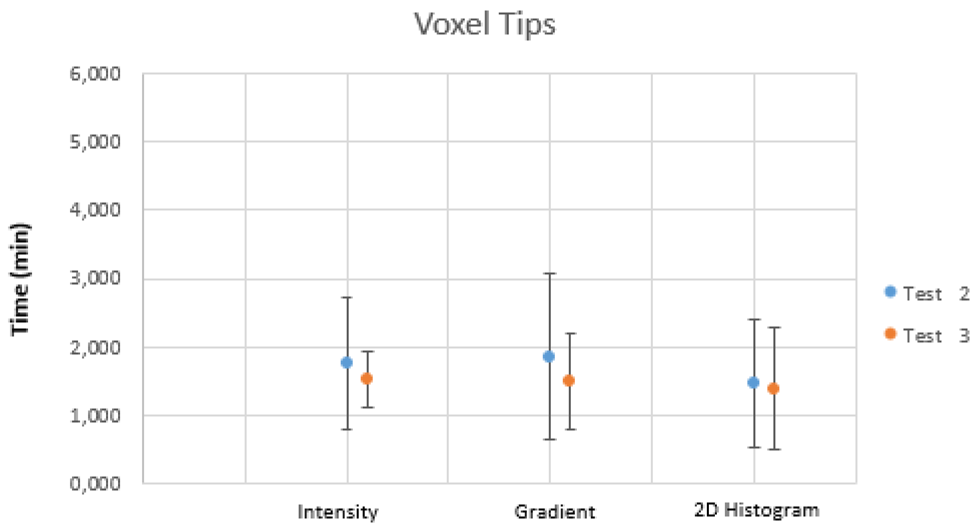


Figure 38. Time required by users to perform each task in test 2 and 3, in both interfaces.

Furthermore, in Voxel Tips we can observe a slight decrease in the time required to perform each task, between test 2 and test 3, especially when compared to the conventional software, where there was no notable improvement between tests when designing the gradient and 2D histogram transfer functions. However, there was a noticeable decrease in the amount of time necessary to design the intensity transfer function in Votracer. This can be due to a lack of familiarity with user interface (Figure 38).

In Voxel Tips the standard deviation is much smaller than the one found in Votracer. The lower consistency of the results found in Votracer could be due to the fact that during the design of the transfer function the users often relied on luck to obtain the desired results. Thus, some users were able to obtain an approximation of the transfer function unknowingly, while others struggled to obtain the same results.

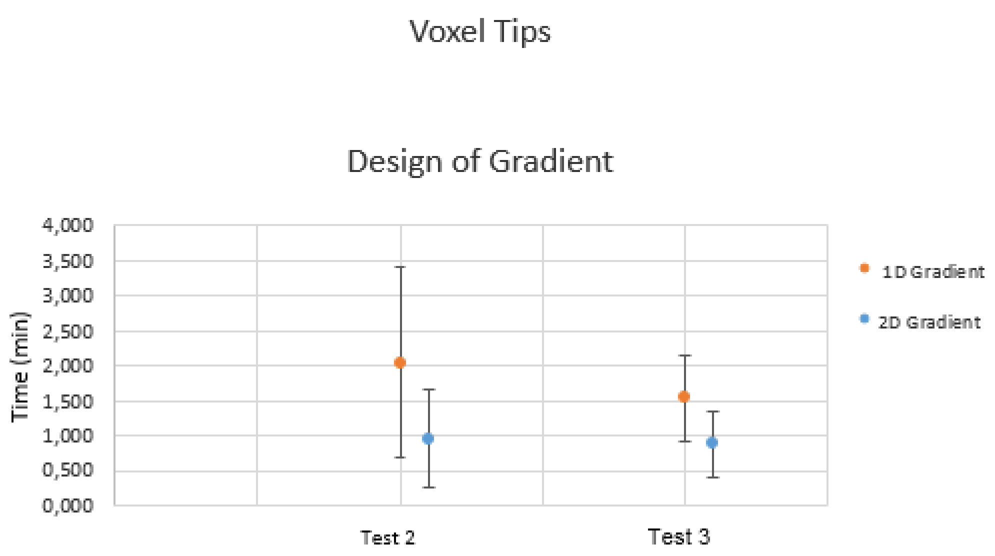


Figure 39. Design of the gradient transfer function with and without the 2D histogram

In Voxel Tips there was a decrease in the time required to draw the gradient function with the 2D histogram (Figure 39). This suggests the users were able to retain some of the knowledge acquired during the inspection of the transfer function domain, and apply it even without the use of the exploration tools provided previously.

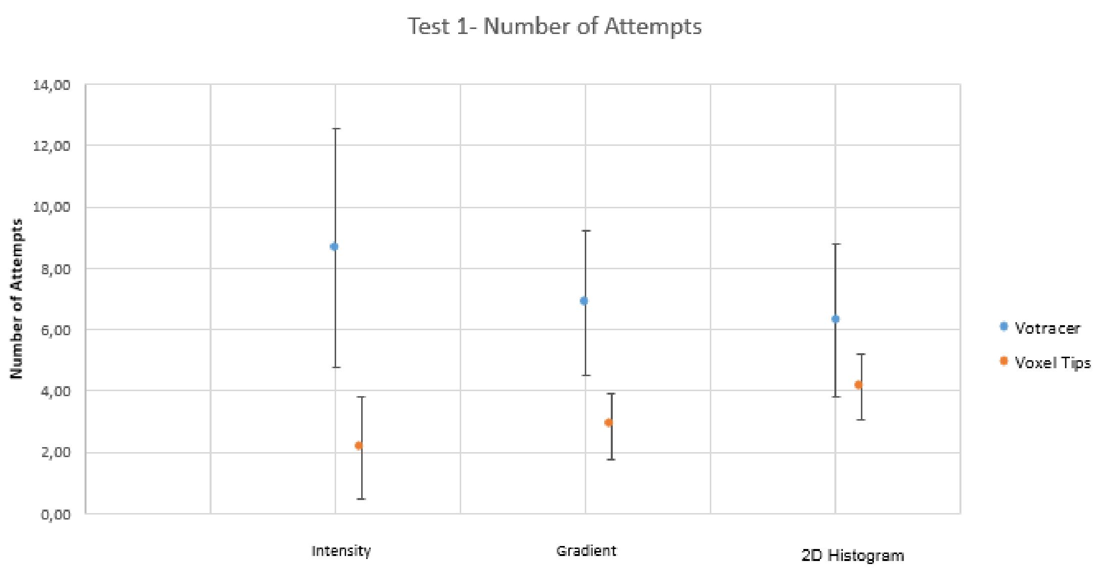


Figure 40. Number of attempts necessary to perform each task in both interface

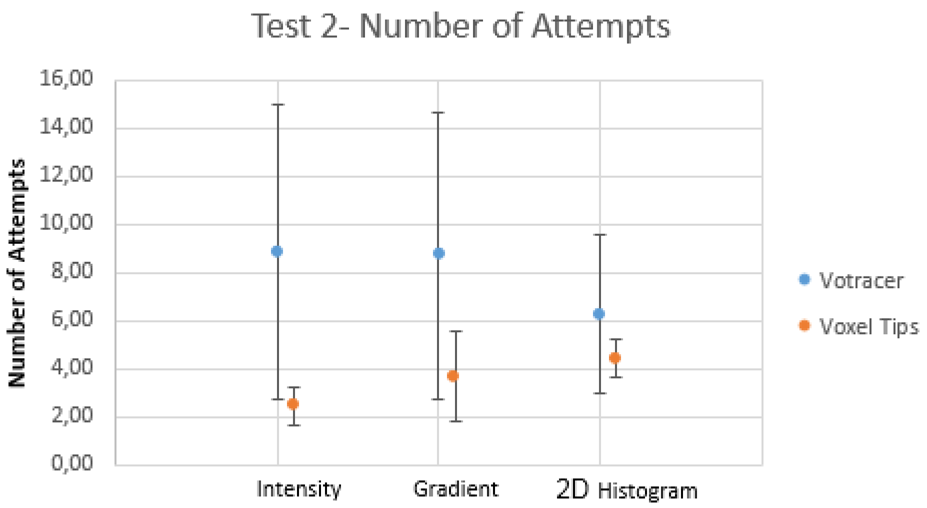


Figure 41. Number of attempts necessary to perform each task in test 2, comparing the results between both interface

The number of attempts needed to obtain the desired transfer functions were determined for a subset of the user base. (Figure 40 and 41)

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

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).

However, there was no noticeable improvement in the number of attempts necessary to obtain the desired function in subsequent tests, using either interface. This can suggest that the amount of time the users were exposed to the interfaces was not enough for them to gather substantial experience with the tools to improve their performance between tests.

5.4 PROFESSIONAL OPINION

As part of this thesis, Voxel Tips was presented to a number of professionals, mainly medical staff, in order to obtain feedback on the application and its usefulness as a medical educational tool.

5.4.1 HOSPITAL PROF. DOUTOR FERNANDO FONSECA, EPE

Voxel Tips was presented to the medical staff in the department of Imagiology at the hospital Prof. Doutor Fernando Fonseca. Most physicians had a very positive reaction when presented to this interface. They considered that Voxel Tips had great potential as a tool for manipulation of images acquired by CT, since it allows the coloring of structures based on its intensity. This would allow physicians to highlight the structure of interest, which facilitates the visualization of an exam, when sometimes a feature is hard to observe as is often the case with deformed structures.

Specifically, in the case of neurogenic bladder dysfunction, where the bladder loses its ability to release urine properly, it can became deformed and hard to recognize in medical images unless by a professional specialized in Imagiology. Thus, the ability to highlight the bladder and observe the structure within the context of the surrounding tissues is of great value, which can be achieved using the tools proposed in this thesis.

It was also suggested that Voxel Tips would be of great value in an educational environment, since it allows students of Medicine to study anatomical structures under pathological conditions and also understand how these structures are related to each other, which is often difficult to achieve with the conventional approach that is taught in Medicine. There was, however, a radiologist who considered that Voxel Tips was more suitable in a more playful environment, particularly its use in museums and scientific illustration. He also observed that in Radiology conventional software offers the opportunity to apply a standard transfer function that isolates a specific anatomical structure, which is often preferred by professionals, even if the results are not optimized.

5.4.2 PROF ANTÓNIO MATOS OF CIIEM

Prof. António Matos suggested that Voxel Tips could be expanded for the visualization and exploration of medical volumes based on X-rays images, allowing to highlight structures that otherwise would be difficult to visualize in a conventional X-ray image.

5.4.3 *Faculty of Science of the University of Lisbon*

Improvements to Voxel Tips were suggested by some members of the faculty of science of the University of Lisbon, namely the ability to select and highlight full organs based on the selection of specific areas and the identification of voxels with similar intensity and gradient as part of the same structure.

CHAPTER VI

6 DISCUSSION OF THE RESULTS

Voxel Tips was determined by the users as the preferred interface to visualize and manipulate volumes, which was corroborated by the results that users achieved when performing tasks in this interface.

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 same does not happen in Votracer, where a function design is done freely within the domain and with no specific structure for data analysis, which results in a higher number of attempts and much greater variability of the results, especially since we are dealing with a set of users with no experience in transfer function design. For example, users would often discover a suitable transfer function by accident instead of by analyzing and understanding the function domain.

A longer habituation period may be necessary to decrease the random elements associated with Votracer, but since Voxel Tips is meant to be used by people with little or no experience, tests must be performed in similar conditions. Thus, the random element in Votracer must be considered as a limitation that can be present in any transfer function design and tools developed in this area must take this into account.

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.

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. Touch controls produced a much better result when designing a transfer function since they more accurately reproduce the users intentions.

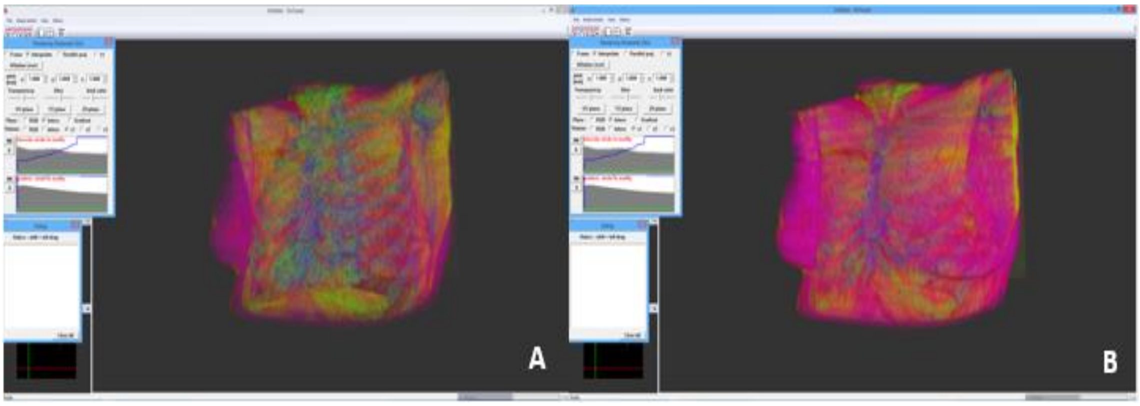


Figure 42. Innacurate feedback from the volume perceived during the users. (A) Before dropping the mouse. (B) After dropping the mouse

Another difficulty that users found when dealing with Votracer was the inaccurate feedback from the volume, specifically, the volume would have a different appearance before and after the user released the mouse button (Figure 42).

This is due to a change in the resolution of the image while the transfer function is being drawn, and it is not uncommon in volume rendering software. Regardless, this aspect, along with the difficulties in designing the transfer function, can explain the worst results associated with Votracer.

Since Voxel Tips is directed towards users that may or may not have some background in dealing with medical images, the users chosen to participate in these tests had a variety of backgrounds. Surprisingly, there was no noticeable difference between users with different backgrounds, which may indicates that the tools presented do an adequate job at providing the users with the necessary information to perform each task, regardless of their level of knowledge regarding medical images or visual filters.

However 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.

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. Other limitations come in a form of a lack of an easy and simple way of controlling the opacity attributed to the selected areas, which may have led to a better exploration of the domain data and a better and more visually appealing results.

When assigning color to the transfer function domain, the main limitation that had a negative effect on user experience was the slow response of the application to the users input. This is mainly a performance problem due to the use of non-optimized code as a result of limited background during the development of this interface. However, despite this limitation, users still have some trouble in stablishing a relationship between the color assignment and the intensity values.

This may be due with the lack of visual culture or even of a lack of familiarity with the color assignment concept. This difficulty was very evident in most users, especially those that had no Informatics background. One way of possibly solving this problem is by giving the user a better feedback of how the color is assign to values of transfer function domain, such as assigning color to the histogram or the thumbnails.

Despite these difficulties, 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 (Figure 43).

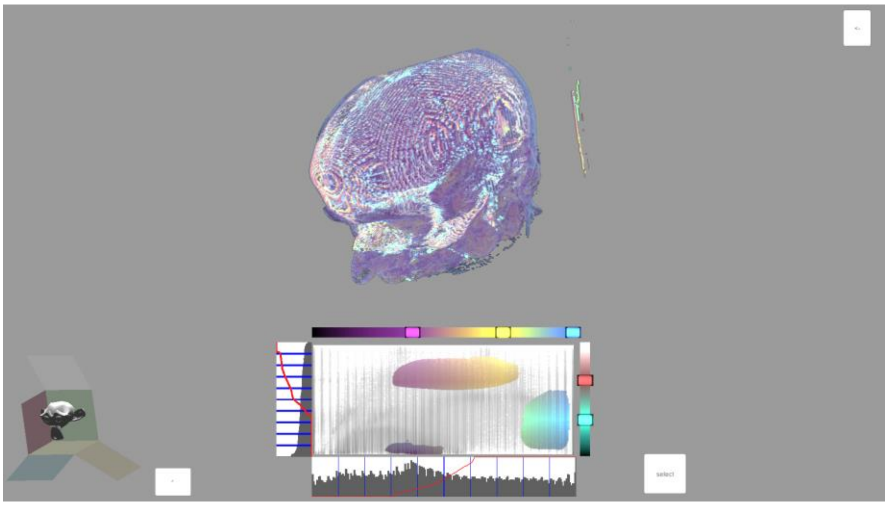


Figure 43. Color mapping on the selected areas of 2D histogram.

This provides an alternative to the benefits presented by Votracer's exploration of the domain since users can explore the data not by manipulating opacities but by manipulating colors. This, however, was not tested and maybe the basis for a new set of tools for data exploration, which is not the subject of this thesis.

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. However, it presented some problems, namely performance issues due to the use of non-optimized code and bad memory management, the use of hardware that sometimes was unable to meet the system requirements and the use of volume rendering techniques that limited development and presented several artifacts.

Several improvements can also be made in order to make Voxel Tips graphically more appealing, which requires higher technical expertise that what was available during the development of this thesis.

CHAPTER VII

7 FUTURE WORK AND CONCLUSIONS

7.1 FUTURE WORK

7.1.1 GENERAL APPLICATION IMPROVEMENTS

Some users noticed the slowness in Voxel Tips color selection and in actions controlled by touch. This is due to the fact that the interface is not running on optimized code and thus contains several architecture errors and inefficiencies. These issues may be solved by a code restructuring carried out by a developer with an Informatics background.

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.

In order to make this interface more similar to the interfaces that are used in a medical environment, making it more familiar and more easily accepted by health professionals, Voxel Tips needs to implement several predefined transfer functions that isolates regions of interest and allows them to be freely modified and optimized using the same set of tools.

7.1.2 Clustering Algorithms for transfer function design

When using 2D histograms some problems may arise related to the combination of intensity value and gradient magnitude, where sometimes boundaries appear as arches that frequently overlap causing classification ambiguities.

In order to fill this gap, a new way of isolating structures of interest without having to use the 2D histogram, based on the computation of the magnitude of the gradient, is a desired solution. In the field of semi-automatic design of transfer functions an approach that generates clusters in the transfer function domain could be developed to this end. (Vilanova and Gerritsen, 2006) This approach is used to visualize material boundaries and is based on clusters that constitute the transfer function for the direct volume rendering. The clustering of material boundaries can be done according to two similarity measures: boundaries in the transfer function domain and their spatial relationship.

7.1.3 Dynamic Thumbnails

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.

7.1.4 CLIPPING PLANES

The ability to manipulate the volume in order to perform clipping planes is available in several volume rendering applications and is a tool of great value for the study of volumetric data. This can be achieved using several different approaches such as the use of tablets and smartphones to perform cuts in the volume according to the position and orientation of the device or the use of hand gestures either with motion tracking devices or touch surfaces.

7.1.5 TOUCH DETECTION

The fact that touch position is detected through an array of infrared sensors, instead of a touch detection surface, can lead to some problems when the user is performing his/her selection, since the infrared sensor may be unintentionally blocked by a sleeve or any other part of the body other the selection finger. Thus, to solve this problem, new touch detection technologies need to be used or, alternatively, new touch detection algorithms need to be implemented to account for unintended interactions.

7.1.6 SURGICAL APPLICATIONS

An interesting use of Voxel Tips would include surgical planning. Surgeons, while medical experts, have limited experience and knowledge in dealing with computer interface and function design. Nowadays they can benefit from accurate volume representations of patients anatomical structures, but flexible visualization and interaction is needed to observe each individual case, but a strong guidance is still needed, since physicians usually do not have the technical capabilities to freely and effectively explore and interpret 3D data. In order to help with this limitation and make this interface usable for surgical planning, features need to be implemented, in order to satisfy the requirements below (Mühler et al., 2010):

- The interface must be provided to support distance, volume and angle measurement, since this measures are closely connected to surgical decisions.
- The interface has the need of integrating 2D and 3D visualizations: 2D and 3D views should be synchronized and coherent, with interaction facilities in both views but the exploration of 3D data should be supported in particular.
- The interface needs to include anatomical context in the visualization of important structures.
- The interface needs to provide defaults for visualization parameters.

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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8 APPENDIX

Questionário - Voxel TIPs

Nº de utilizador:

Género:
Masculino
Feminino

Idade:

Habilitações Literárias:
Ensino Secundário
Licenciatura
Mestrado
Doutoramento

Qual a sua mão dominante?
Direita
Esquerda

Que tipo de formação escolar ou académica possui? (ex. engenharia, medicina, arquitectura)

Em média, com que frequência utiliza dispositivos multitoque?
1 vez por semana
2-5 vezes por semana
1 vez por dia
2-5 vezes por dia
> 5 vezes por dia

Classifique o seu nível de experiência em manipulação de imagens médicas?
1 – Nenhuma
2 – Básica
3 – Razoável
4 – Profissional

Design da Função de transferência 1D

Foi fácil obter um resultado semelhante ao pretendido?

	1 - Díficil	2	3	4 – Fácil
Figura 1				
Figura 2				

Atribua um grau de dificuldade a cada uma das funcionalidades nos exercícios relativos à aproximação inicial da função transferência 1D.

	1 – Díficil	2	3	4 – Fácil
Janela Deslizante				
Cursores Deslizantes				

Quão eficaz foi cada uma das funcionalidades na obtenção do volume desejado?

	1 – Díficil	2	3	4 – Fácil
Janela Deslizante				
Cursores Deslizantes				

Qual das funcionalidades prefere na aproximação da função transferência 1D?

Janela Deslizante

Cursores Deslizantes

Atribua a dificuldade sentida no desenho da função transferência com a funcionalidade do esboço.

1 – Díficil

2

3

4 - Fácil

Classifique a compreensão da relação entre o domínio da função e o volume gerado.

1 – Má

2

3

4 - Boa

Aplicação de Cores

Atribua a dificuldade sentida na selecção da cor desejada

1 – Má

2

3

4 - Boa

Atribua a dificuldade sentida na atribuição de cor à estrutura de interesse.

1 – Má

2

3

4 - Boa

Considera que a selecção de cores apresentada é de fácil utilização? Se não, porquê?

Outras sugestões:

(Apresente modificações que consideraria úteis na evocação e atribuição de cores)

Design da Função de Gradiente 1D

Design da Função de Transferência 2D sem histograma 2D (2 telas horizontais: Intensidade e Gradiente)

Foi fácil obter um resultado semelhante ao pretendido?

	1 - Díficil	2	3	4 – Fácil
Figura 1				
Figura 2				

Atribua um grau de dificuldade a cada uma das funcionalidades nos exercícios relativos à aproximação inicial da função de gradiente 1D.

	1 – Díficil	2	3	4 – Fácil
Janela Deslizante				
Cursores Deslizantes				

Considera que as funcionalidades apresentadas para auxiliar o desenho da função do gradiente são úteis?

1 – Inútil

2

3

4 - Útil

Qual das funcionalidades prefere na aproximação da função gradiente 1D?

Janela Deslizante

Cursores Deslizantes

Atribua a dificuldade sentida no desenho da função gradiente com a funcionalidade do esboço.

1 – Fácil

2

3

4 - Difícil

Classifique a compreensão da relação entre o domínio da função e o volume gerado.

1 – Má

2

3

4 - Boa

Design da Função de Transferência 2D

Design da Função de Transferência 2D com histograma 2D

Foi fácil obter um resultado semelhante ao pretendido no desenho da função do gradiente?

	1 - Díficil	2	3	4 – Fácil
Figura 1				
Figura 2				

Atribua a dificuldade sentida no desenho da função gradiente com o histograma 2D

1 – Difícil

2

3

4 - Fácil

Foi fácil obter um resultado semelhante ao pretendido na selecção de áreas?

	1 - Díficil	2	3	4 – Fácil
Figura 1				
Figura 2				

Atribua a dificuldade sentida na seleção das áreas do histograma 2D.

1 – Difícil

2

3

4 - Fácil

Classifique a compreensão da relação entre o domínio da função e o volume gerado.

1 – Mau

2

3

4 - Bom

Em quais dos casos obteve o desenho da função gradiente mais próxima da desejada?

Função Transferência 2D sem histograma 2D

Função Transferência 2D com histograma 2D

Em quais dos casos sentiu maior facilidade em desenhar correctamente a função de gradiente?

Função Transferência 2D sem histograma 2D

Função Transferência 2D com histograma 2D

Função de Intensidade 1D + Função do Gradiente 1D vs Função 2D

Em qual delas conseguiu obter os melhores resultados?

	Função de Intensidade 1D+ Função do Gradiente 1D	Função
Figura 1		
Figura 2		

Em qual delas conseguiu reproduzir da melhor forma a sua intenção de selecção?

	Função de Intensidade 1D+ Função do Gradiente 1D	Função
Figura 1		
Figura 2		

Em qual delas conseguiu obter mais facilmente a função de gradiente pretendido?

	Função de Intensidade 1D+ Função do Gradiente 1D	Função
Figura 1		
Figura 2		

Com que ferramentas obteve uma melhor compreensão dos dados?

	Função de Intensidade 1D+ Função do Gradiente 1D	Função
Figura 1		
Figura 2		

Transformações Geométricas

Qual o nível de dificuldade na execução das seguintes transformações espaciais sobre o modelo?

	1 -Difícil	2	3	4 – Fácil
Translação				
Zoom				
Rotação Livre				
Rotação na horizontal				
Rotação na vertical				
Rotação em torno do eixo perpendicular que sai da mesa				

Considera que a "caixa aberta" facilitou a manipulação e exploração do modelo?

1 – Nada

2

3

4 - Bastante

Considera que o comando de reset era de fácil utilização?

Sim

Não

Tem sugestões de outros padrões de interacção multitoque para desempenhar estas tarefas?

GUI (Graphical User Interface)

Considera que a interface possui um número adequado de botões?

Sim. Tem o número adequado de botões.

Não. Apresenta um número de botões insuficiente.

Não. Apresenta botões em excesso.

A interface tem uma disposição ("layout") de botões coerente?

1 – Confuso

2

3

4 - Coerente

Foi fácil identificar a função de cada botão?

1 – Difícil

2

3

4 - Fácil

Considera que as dimensões do "sketchpad" são apropriadas para as tarefas que desempenhou?

1 - Pouco apropriadas

2

3

4 - Muito apropriada

Considera que as miniaturas contribuem para uma visualização geral do conteúdo do volume?

1- Contribuem pouco.

2

3

4 - Contribuem bastante.

Considera que existe informação em falta? Se sim, qual?

Tem algum comentário em particular sobre a GUI?

(Qualquer comentário construtivo é sempre bem-vindo!)

Geral

Como classificaria o nível de dificuldade geral no uso do sistema?

1 – Difícil

2

3

4 - Fácil

Há alguma funcionalidade que considera fazer falta nesta aplicação? Se sim, qual?

Outras sugestões:

Questionário do Software Convencional

Número de utilizador

Design Função Transferência 1D

Que dificuldade atribuiria à determinação da aproximação inicial da função transferência?

	1 - Difícil	2	3	4 – Fácil
Figura 1				
Figura 2				

Como classifica a aproximação da função transferência para a obtenção do volume final?

	1 - Difícil	2	3	4 – Fácil
Figura 1				
Figura 2				

A relação entre o domínio da função de transferência e o volume gerado é de fácil compreensão?

1 – Má

2

3

4 - Boa

Design da Função de Gradiente 1D

Como classifica a aproximação da função gradiente para a obtenção do volume final?

	1 - Difícil	2	3	4 – Fácil
Figura 1				
Figura 2				

Que dificuldade atribuiria à determinação da aproximação inicial da função gradiente?

	1 - Difícil	2	3	4 – Fácil
Figura 1				
Figura 2				

A relação entre o domínio da função de gradiente e o volume gerado é de fácil compreensão?

1 – Má

2

3

4 - Boa

Design da Função de Transferência 2D

Design da Função de Transferência 2D com histograma 2D

Foi fácil obter um resultado semelhante ao pretendido?

	1 - Difícil	2	3	4 – Fácil
Figura 1				
Figura 2				

Atribua a dificuldade sentida na seleção das áreas do histograma 2D.

	1 - Difícil	2	3	4 – Fácil
Figura 1				
Figura 2				

Classifique a compreensão da relação entre o domínio da função de transferência e o volume gerado.

1 – Má

2

3

4 - Boa

Transformações Geométricas

Qual o nível de dificuldade na execução das seguintes transformações espaciais sobre o modelo?

	1 -Difícil	2	3	4 – Fácil
Translação				
Zoom				
Rotação Livre				
Rotação na horizontal				
Rotação na vertical				
Rotação em torno do eixo perpendicular que sai da mesa				

GUI (Graphical User Interface)

O que sente em relação à quantidade de botões na interface?

1 – Poucos

2

3

4 - Muitos

A interface tem uma disposição ("layout") de botões coerente?

1 – Confuso

2

3

4 - Coerente

Foi fácil identificar a função de cada botão?

1 – Difícil

2

3

4 - Fácil

Considera que existe informação em falta? Se sim, qual?

Tem algum comentário em particular sobre a GUI?

Geral

Como classificaria o nível de dificuldade geral no uso do sistema?

1 – Difícil

2

3

4 - Fácil

Há alguma funcionalidade que considera fazer falta nesta aplicação? Se sim, qual?

Outras sugestões:

Questionário final

Questionário a ser preenchido após o preenchimento do Voxel Tips e do Votracer.

Número de utilizador

Design das Funções Transferência 1D

Com quais das funcionalidades prefere efectuar a aproximação da função transferência 1D?

Janela deslizante,Cursores deslizantes (Voxel Tips)

Desenho directo (Software Convencional)

Comparativamente ao software convencional, considera que as miniaturas do Voxel Tips apresentam uma mais valia no desenho da função transferência?

Sim

Não

Que tipo de input prefere para o desenho da função transferência.

Teclado+Rato

Superfície Touch

Design das Funções Gradiente 1D

Com quais das funcionalidades prefere efectuar a aproximação da função gradiente 1D?

Janela deslizante,Cursores deslizantes (Voxel Tips)

Desenho directo (Software Convencional)

Que tipo de input prefere para o desenho da função gradiente.

Teclado+Rato

Superfície Touch

Design das Funções Transferência 2D

Comparativamente ao software convencional considera que o Voxel Tips se apresenta como uma mais valia no desenho de uma função transferência 2D?

Sim

Não

Em que interface a função 2D permitiu uma melhor exploração dos dados?

Voxel Tips

Software Convencional

Em que interface a função 2D permitiu um melhor controlo das opacidades?

Voxel Tips

Software Convencional

Que tipo de input prefere para o desenho das funções transferência?

Teclado+Rato

Superfície Touch

Transformações Geométricas

Que controlos prefere na manipulação do volume?

Teclado+Rato

Controlo Touch

Onde considera mais fácil a manipulação de volumes?

Voxel Tips

Software Convencional

Há alguma característica/funcionalidade presente numa aplicação que achou estar em falta na outra? Se sim, qual (quais)?

TERMO DE AUTORIZAÇÃO DE USO DE IMAGEM

Eu, ____, portador(a) do Cartão do Cidadão nº ____________. AUTORIZO a captura e utilização da minha imagem na realização dos testes de utilizador no âmbito da tese "Transfer Function Design for Three-Dimensional Medical Images Using Sketches" no Instituto Superior Técnico.

A presente autorização cede ao grupo de investigação Vimmi o direito de utilizar a gravação acima referida para fins académicos e de investigação sem nunca ceder a terceiros.

Professor Joaquim Jorge | Assinatura

__________________________ | __________________________

Guião do Voxel Tips

Controlos

O controlo do volume é feito por toques e verifica vários tipos de interacção:

- Translação: O volume é arrastado pelo ecrã utilizando os 5 dedos da mão
- Rotação em torno de um eixo: Um dos dedos fixa o eixo de rotação (pivot) e o outro descreve paralelamente a este o movimento de rotação do volume.
- Zoom in: Utiliza as duas mãos, nomeadamente os dois indicadores. Se afastar os indicadores promovo um aumento de detalhe apresentado no volume.
- Zoom out: Utiliza as duas mãos, nomeadamente os dois indicadores. Se aproximar os dois dedos, promovo uma diminuição no detalhe do volume.
- Rotação Horizontal e Vertical: Levadas a cabo por um dedo movimentando-se horizontalmente ou verticalmente, respetivamente.
- Comando de reset: Efectuado por um dedo que bate consecutivamente na mesa 3 vezes.

Open box

Disposta no canto inferior esquerdo da GUI do Voxel Tips. Consiste num cubo, com uma cabeça de macaco integrada como referência espacial, de forma a que premindo uma das faces do cubo, o volume apresente uma posição referente aos eixos canónicos.

Funções Intensidade

De forma a manipular as intensidades é apresentada uma tela, localizada na parte inferior do GUI do Voxel Tips, que se encontra dividida em 10 segmentos, cada uma deles correspondendo a um intervalo de intensidades. A cada um destes segmentos, corresponde uma renderização dos voxels dentro do intervalo de intensidades, estando esta localizada imediatamente abaixo do respetivo segmento. A estas renderizações damos o nome de thumbnails.

Com o propósito de auxiliar o design da função de transferência existe um conjunto de ferramentas, que são oferecidas na forma de um menu de quatro botões, localizado na parte esquerda das telas da intensidade e do gradiente. A cada um destes botões corresponde uma dada ferramenta: função rampa, janela, réguas e esboço, respetivamente.

Função Rampa

Tenta obter uma abordagem similar à do software convencional. A função é definida pelo utilizador e pode ser movida verticalmente entre a parte superior e inferior da tela. Os valores intermédios entre os dois nós são determinados por interpolação linear, de forma semelhante ao software tradicional

Janela

Trata-se de um sinal quadrático, que permite a inspeção de todo o domínio da função, de forma a que o utilizador possa localizar a informação de interesse no domínio. Toda a informação contida dentro dos limites da janela é apresentada no volume. O utilizador poderá interagir com a janela de duas formas: controlo da opacidade ou através do aumento do seu intervalo de ação. No sentido de controlar a opacidade, o utilizador tem apenas de controlar a altura da janela através de um dos círculos, arrastando-o para cima se desejar aumentar a opacidade da informação em estudo ou arrastá-lo para baixo caso contrário. Quando lidamos com o aumento do seu intervalo de ação, basta interagir com um dos círculos, arrastando-os para a direita ou para a esquerda, consoante desejemos aumentar ou diminuir o comprimento da janela.

Réguas

Cada botão pode ser arrastado ou posicionado a qualquer altura dentro da tela, sendo que a posição do limite superior do botão representa a opacidade a ser atribuída aos valores da função dentro do intervalo desse respetivo botão. Vários botões podem ser movidos simultaneamente, constituindo uma metáfora de um DJ numa mesa de som. As próprias miniaturas podem ser usadas como botões para reduzir a opacidade do intervalo correspondente a zero, ou alternar a opacidade do intervalo entre zero e um (máximo).

Esboço

Como forma de tornar o design da função de transferência mais pessoal, é dada ao utilizador a opção de desenhar livremente qualquer esboço sobre a tela. Uma vez desenhado, este esboço é adaptado e transformado numa diretamente numa função de transferência, aplicada ao volume e seguidamente é representada sobre a tela.

Atribuição de Cor às Intensidades

De forma a proceder à atribuição de cor a estruturas de interesse, duas barras de escala de cinza são posicionadas diretamente acima e abaixo das telas brancas utilizadas para o gradiente e intensidade, respetivamente. A atribuição de cores às intensidades é feita interagindo com a barra superior: quando um é realizado um toque duplo, esta barra irá criar um pequeno cursor que tem uma determinada cor, atribuída através de um seletor de cores. Pressionando o cursor uma vez, este abre ou fecha a tela de seleção de cores. A cor selecionada é aplicada ao cursor em tempo real, e a cor é atribuído ao volume. A posição do cursor na barra irá indicar o valor do domínio de que a cor é aplicada ao, e depois interpolada até aos limites de barras ou de outras cores atribuídas, se outros cursores estão presentes. A eliminação de cores é feita arrastando os cursores do lado de fora do bar e deixá-los cair. Se o cursor é arrastado para uma outra posição dentro da barra, este adquire a posição desejada na barra.

Se for arrastado para um segmento da tela de intensidades, dois cursores serão criados e colocados nos limites da faixa onde o cursor foi largado. Assim todo este intervalo de intensidades irá apresentar a mesma cor.

A barra de escala de cinza inferior é utilizada apenas como uma referência às cores originais dos dados de volume.

Função de Transferência dos Gradientes

Assemelha-se em tudo ao processo acima descrito para as intensidades, com a exceção da opacidade dos réguas serem controlados pelas miniaturas, uma vez que estas apenas estão afetas às intensidades e não aos gradientes. Nesse sentido, o controlo da opacidade das réguas irá adquirir a posição de toque para a atribuição das opacidades.

Histograma 2D

Na cena do histograma 2D é utilizada uma tela para exibir um histograma 2D. O histograma apresenta uma forma típica para representar materiais e fronteiras entre esses materiais, que são representados como pontos circulares e formas de arcos, respetivamente. A fim de criar uma familiaridade com o design função de transferência 1D (função intensidade 1D e gradiente 1D), as telas da função intensidade e da função de gradiente são exibidas horizontalmente e verticalmente. Assim, o utilizador pode ter uma melhor compreensão do histograma 2D e da área de que necessita para selecionar. Para além da atribuição de cores às intensidades (barra de tons de cinza superior) também se verifica uma atribuição de cor para a contribuição gradiente (barra em tons de cinza localizada lateralmente ao histograma. O utilizador executa a seleção da área manualmente, desenhando o perímetro da área de seleção desejada. A área é definida uma vez detetada a colisão da linha , fechando assim a área de seleção. Todos os pontos dentro da seleção possuem opacidade máxima e os pontos fora da seleção possuem uma opacidade zero. Existe ainda a possibilidade de alternar entre a função de seleção e deleção, que é dada por um botão localizado lateralmente ao histograma.