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ORIGINAL ARTICLE

Explicit design of transfer functions for volume-rendered images by combining histograms, thumbnails, and sketch-based interaction

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Abstract Visual quality of volume rendering for medical imagery strongly depends on the underlying transfer function. Conventional Windows–Icons–Menus–Pointer interfaces typically refer the user to browse a lengthy catalog of predefined transfer functions or to pain-staking refine the transfer function by clicking and dragging several independent handles. To turn the standard design process less difficult and tedious, this paper proposes novel interactions on a sketch-based interface that supports the design of 1D transfer functions via touch gestures to directly control voxel opacity and easily assign colors. User can select different types of transfer function shapes including ramp function, free hand curve drawing, and slider bars similar to those of a mixing table. An assorted array of thumbnails provides an overview of the data when editing the transfer function. User performance is evaluated by comparing the time and effort necessary to complete a number of tests with sketch-based and conventional interfaces. Users were able to more rapidly explore and understand volume data using the sketch-based interface, as the number of design iterations necessary to obtain a desirable transfer function was reduced. In addition, informal evaluation sessions carried out with professionals (two senior radiologists, a general surgeon and two scientific illustrators) provided valuable feedback on how suitable the sketch-based interface is for illustration, patient communication and medical education.

Keywords Transfer function · Volume rendering · 3D medical images · Sketch-based interfaces · Thumbnails · User study

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1 Introduction

When generating volume-rendered medical images, the design of transfer functions must be performed in a comprehensive and well-structured manner to effectively communicate anatomical and physiological information. The graphical quality of the rendered image strongly depends on the transfer function applied to the volume data, which is expected to contrast the many subject-specific anatomical structures.

However, finding an appropriate opacity and color mapping to a given volume data set is not a trivial task. Transfer functions and the associated histogram are inherently nonspatial (i.e., neither the function domain nor its codomain are geometrical quantities). This increases the difficulty of mapping the transfer function domain to a specific anatomical structure as they are not readily distinguishable in terms of voxel intensity [14]. There have been attempts to overcome this issue by including position dependency to transfer function parameter [2] or by adding spatial information to the histogram of a volume [24], although they do not entirely solve the issues outlined by the authors. Moreover, it has been reported that many users of interactive volume rendering software do not have the required visual skills nor the expertise necessary to obtain good visual quality results in a timely manner [1,22]. If the anatomical structure of interest is not well isolated under a predefined transfer function, then the user is left to the arduous trial-and-error tasks to find a suitable transfer function.

Conventional volume rendering software enables users to browse a lengthy catalog of predefined transfer functions. Such task is usually intended to quickly isolate specific tissues for very concrete image modalities or body regions. However, a catalog may not be properly optimized, thus, leaving the user to further edit the functions to fit specific radiological cases through a Windows–Icons–Menus–Pointer (WIMP) interface. The design of the transfer function through a WIMP interface is not fluid or easy to perform [6,12], since it often requires dragging several handles with a mouse, one at a time, to obtain the desired transfer function shape. Moreover, mouse-based interfaces are not tailored for expressing initial concepts, thus, hampering user's drawing performance to quickly deliver an initial design or propose several alternative transfer functions.

Given the inherent challenges of direct edition of transfer function and the limitations of WIMP approaches, more natural and simpler interaction techniques, such as those promoted by sketch-based interfaces, are welcomed to better understand volume content and enhance design efficiency. However, direct edition of transfer functions is a research topic that has not been very addressed by the visualization community.

In this work, we propose a sketch-based interface and novel interaction approaches to directly control voxel opacity and to freely design transfer functions for an arbitrary volume data set. The scope of our work consists of direct edition of transfer functions, i.e., users explicitly draw 1D graphs to globally or locally define intensity- or gradient-based transfer functions. The main goals are to reduce the amount of time, number of tentative trials and efforts, which typically characterize standard mouse-based transfer function design, by manually drawing the function shape via a sketch-based interface. We make use of an interactive surface and propose new ways of effectively designing transfer functions trough sketches and touch gestures. A user study was conducted to verify whether the proposed interactive approach performs better than conventional WIMP systems. Informal evaluations were also conducted with illustrators, biomedical engineers and medical practitioners to ascertain whether the sketch-based approach is useful in different medical scenarios such as illustration, patient communication, and medical education.

2 Related work

Conventional volume rendering software such as Voreen (www.uni-muenster.de/Voreen), Inviwo (https://www.inviwo.org/), OsiriX (www.osirix-viewer.com), Volview (https://www.kitware.com/volview/) and Paraview (www.paraview.org) follow a WIMP approach. Users are invited to characterize anatomical structures by selecting predefined 1D transfer functions from a predetermined catalogue. Normally, users require further function shape editing. This is accomplished by resetting the position of several handles throughout the histogram view. Each handle is connected by a straight or curved line, usually having a ramp-like or trapezoidal appearance. Other WIMP software tools such as VoTracer (www.riken.jp/brict/Ijiri/VoTracer) enables the user to directly sketch the function using the mouse pointer, although the resulting function is non-smooth and very jittery.

More advanced interfaces have addressed transfer function design by promoting indirect edition of the underlying opacity mapping. For instance, different approaches aim for indirect transfer function design through the use of thumbnails. Design galleries [21] consists of several thumbnails displayed in a 2D layout. Users can then choose and drag selected thumbnails to the surrounding image gallery in order to make more conscious decisions dealing with transfer functions. König et al. [16] proposed a similar approach by providing the user with an arranged display of previews, allowing him to choose a region to work as an initial set of parameters for fine-tuning. While most work on transfer function design rely on image processing techniques [4,9,11,15,18–20,23,26], there have been some interesting ideas regarding sketch-based approaches. Differences concern exposing the user to 1D or 2D histograms, the use of thumbnails, providing intensity and gradient transfer functions or even enabling direct transfer function design.

Some sketch-based works have made histogram information available for the user [13,25,28]. In order to enable a full assessment of the data set, Jönsson et al. [13] proposed a method for volume exploration based on the use of dynamic galleries. By splitting the domain into equal sub-ranges, the user can decide which of those are important in the visualization based on their respective previews. New previews are dynamically generated as one-dimensional parameter changes occur, allowing a direct, though limited, transfer function editing, in an attempt to decrease the interaction to do so. Also exposing the user to the direct volume rendering (DVR) transfer function, although not permitting direct editing, Wu and Qu [28] propose transfer function fusing to produce a comprehensive result based on different features selected by the users in automatically or semiautomatically generated DVRs. Ropinski et al. [25] proposed an interaction where the user can draw one or more strokes along an outline of the feature of interest, automatically generating a 1D transfer function. Based on the drawn strokes, the range of intensity values that most likely represent the feature of interest are identified, generating a component function. The user can then manipulate color and opacity of each identified component using a layer concept inspired interface.

Also relying on the tendency that users have to pinpoint structures or specific positions on the screen, the sketch-based What You See Is What You Get (WYSIWYG) approach proposed by Guo et al. [7] presents the user with a number of tools that enable DVR manipulation by brushing strokes on top of the rendered volume. This goal-oriented volume exploration does not resort to direct tuning of transfer function parameters, leveraging semantic realization in order to convert the feature inference into a new transfer function and gradually updating the volume rendering, hiding all transfer function and histogram related information from the user. Guo and Yuan [8] further developed this work by proposing a novel volume visualization system that enabled local transfer functions specification. The main difference from the previous global WYSIWYG technique was the introduction of locality, achieved through a pre-processing stage that extracts the abstract topology of the raw volume data, which is partitioned into different topological regions. This way the user can explore and apply effects on topological local features, using painting and sketching combined with gesture interactions. As a result, disconnected features with similar numerical properties can be distinguished by their locations, eliminating the global transfer function limitation. However, not only contour topology is highly dependent on low noise data to perform well, but this system also as a limited number of local topological regions which may hamper the partitioning of different components.

Other WIMP approaches share similar perspectives. Wiebel et al. [27] developed a What You See is What You Pick (WYSIWYP) approach that allows the user to pick 3D structures visible in DVR images. A visibility-oriented picking criterion is used to select the interval boundaries that contribute the highest amount of opacity, which correspond to the interval that is dominantly perceived at the picked screen position. Although non-expert users may consider this type of indirect transfer function manipulation more intuitive, the understanding of the transfer function mapping to image space is severely hampered, not responding to the needs of expert users that aim at improving their transfer function design based on that information.

Finally, Hurter et al [10] aimed at addressing the problem of occlusion that occurs during the exploration of dense multivariate datasets. Color-tunneling consists in a mouse-based set of techniques that creates real-time interactive, animated exploration of datasets. The proposed system presents a set of linked views that display subsets of data attributes, as these views are linked by brushing or free-form selection. The animation creates a sequence of intermediate frames that help the user preserve the "mental map" and visually track patterns of interest. Here, the user benefits from being able to associate spatial information to histogram views which are defined as spatial rearrangements of voxels. Yet, color-tunneling follows an "all-or-nothing" approach, since selected voxels are either maintained or removed. Intermediate transparency values are not permitted. If the user could sketch the transfer function on top of the histogram view, this would lead to more interesting visualizations as it would combine voxel selection/removal with voxel transparency editing.

In short, while other advanced interfaces allow users to implicitly define the transfer function, none really grants the possibility to explicitly draw, tweak, locally refine or globally define the transfer function at any point or interval. Other sketch-based interfaces have been proposed [7,8,13,25,28] but none was tailored for direct transfer function edition as local edition or fine-tuning was not made available, neither have they explored the potential of a stroke to draw transfer functions. Hurter et al. does provide sketch-based interactivity but rather for intensity-based selection or removal, not for editing the transfer function per se. To the authors knowledge, it is the only work where histograms and thumbnails are part of a sketch-based interface to directly edit intensity- and gradient-based transfer functions.

3 Sketch-based interface

The proposed interface is called Voxel TIPs, and it uses a multi-touch table top (Fig. 1c) composed by a large-scale television (Samsung UE55F8000: 55" F8000 Series 8 Smart 3D Full HD LED TV), horizontally placed at waist height ($\sim$ 95 cm above the floor), and a multi-touch sensor system with several arrays of infrared sensors framing the TV border (ZaagTech X Series 16 Touch Overlay). Touch gestures are detected when fingers block infrared beam paths between LEDs and receivers. All software was developed in Unity (C# scripting, GLSL shaders) and run with Windows 7 operating system. Volume rendering of medical images was performed using a conventional ray marching algorithm that stored the projection data as a 3D texture (http://www.it-medex.inesc-id.pt/project/rengine).

The graphical user interface (GUI) consists of three interactive areas (Fig. 1). The upper area is dedicated to display images obtained by volume rendering techniques. By interacting with the screen, the user can translate, rotate and scale the volume data through touch gestures. The bottom white screens, divided into ten equally sized segments, are for sketching and editing the transfer function shapes. To assist the design process, histograms representing intensity or gradient magnitude values are presented on the background and an array of intensity-based thumbnails are displayed at the bottom of the screen. There are color and grayscale bars above and below the white screens, respectively. The color bar depicts the current color map of the transfer function, while the bottom gray scale bar is used solely as a reference to the original intensity grayscale values of the volume data. Assignment of colors is done by interacting with the top bar.

The GUI also displays a set of buttons directly to the left (intensity) and the right (gradient magnitude) of the white screens. These buttons are for selecting different types of editing modes: ramp-like, sliding window, multiple sliders and sketching tool, respectively, from top to bottom. Each slider has a volume rendering thumbnail on the bottom which represents a sub set of intensity values. The rendered image follows the same rotation transformations applied to the main content of the upper area.

3.1 Interaction

Interaction with the Voxel TIPs system follows a symmetric bimanual model [17]. In this case, the system does not require hand dominance. Touch gestures perform several tasks, namely, geometric transformations (i.e., rotation, translation, and scale), selection (e.g., color, thumbnail, function shape), graph sketching and editing.

By interacting with the upper screen area, users can apply geometric transformations using several types of touch gestures: (a) one tap and drag for angle-center rotation; (b) two taps and press and revolve for rotation along the axis orthogonal to the screen plane; (c) pinching or press and drag with two fingers for uniform scale; (d) multi-touch drag for translation; and (e) three or more consecutive taps to reset position and orientation state.

As for interaction on the lower screen areas, users can design the transfer functions by tapping for evoking color handles, selecting shape modes or intensity ranges of interest (thumbnails), and tapping and dragging for sketching 1D graphs, selecting HSV color values, shifting or removing color handles over the color bar or sliding transparency values in the mixing table.

Color is assigned by double tapping the color bar which evokes a handle and color picker with hue saturation value. The selected color is applied to the handle, as a visual cue, and the handles' position sets the color interpolation between the neighboring handles to be assigned to the previous color map. Tapping the handle will open/close the color picker. Dragging and dropping the handle outside the color bar area deletes the handle. If the handle is dropped elsewhere on the bar, it will change the handle's position.

3.2 Transfer function design

Several sketch-based interaction techniques are proposed to find an initial approximation of the transfer function. In conjunction with histogram information, such techniques aid the user to inspect the domain and, consequently, identify which intervals to assign opacity in order to isolate structures interest. To further refine the design, a sketching tool is provided to directly draw local features or the function entirely. This assortment of tools can be applied independently to the intensity and gradient transfer function (Fig. 1).

When the user exchanges between functionalities, the prior transfer function is adapted to fit the function type of the current tool, retaining part of the initial transfer function. For example, switching from ramp-like function to the sketching tool leaves the transfer function unchanged, while switching from sketching tool to multiple sliders, converts the function into a rectangular pulse train according to the average of the values in the range of each slider.

3.2.1 Sliding window

The sliding window consists of a rectangular pulse with controlled amplitude. It can be used to highlight a selected domain interval by setting a constant opacity value within the interval, outside which the function values are set to zero. Pulse height and width can be easily adjusted by dragging two cursors placed at the top edges. 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 user-adjusted window.

3.2.2 Thumbnails

Besides facilitating the interpretation of the histogram, thumbnails provide a comprehensive description of the data enabling immediate recognition of the main structures contained within the data set. Each thumbnail represents voxels with intensity values belonging to a given bounded interval with a length of 10% of the full parameter domain. By tapping the thumbnail, full opacity is applied to the interval range. Thumbnails are illustrated using particle-based volume rendering, representing a lower resolution version of the original volume as a set of emissive and opaque particles.

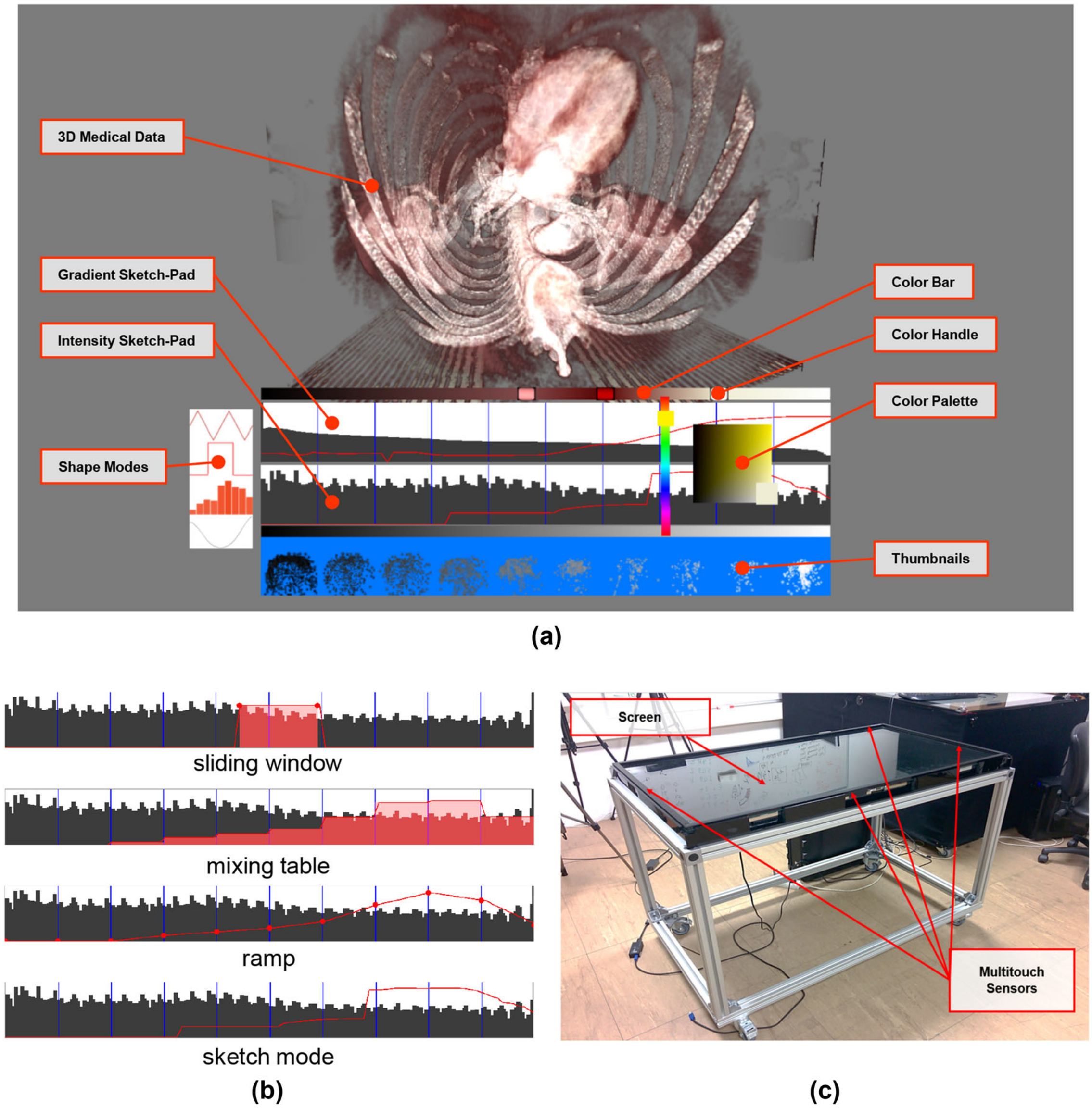

Fig. 1 The Voxel TIPs system: **a** GUI showing three interactive areas and graphical elements, **b** transfer function shape modes (sliding window, mixing table, ramp-like, sketching), and **c** hardware setup

3.2.3 Mixing table

A set of vertical sliders is arranged by associating independent rectangular pulses of adjustable height and fixed to the domain represented with a thumbnail. Several sliders can be moved simultaneously via the multi-touch surface; hence, the interface explores the metaphor of a DJ mixing table. Ten equally sized sliders are placed side-by-side along the transfer function domain. Each vertical slider can be dragged or tapped to a given height. The thumbnails themselves can be used as toggle buttons to set opacity either to zero (minimum opacity value) or one (maximum opacity value). This feature enables the user to select several areas of interest to more quickly obtain an initial approximation of the desired transfer function.

3.2.4 Ramp-like function

The piecewise ramp function is defined by vertically moving linear interpolation nodes, as the intermediate values between each two nodes are determined by linear interpolation. This option was created as an equivalent to the standard transfer function design present in traditional software.

3.2.5 Sketching

Sliding window, thumbnails, mixing table and ramp-like functions are tools to create an initial version or draft of a transfer function. To further refine the function, a sketching tool is required to freely draw any function on the sketch-pad. Each stroke updates the function at the selected domain

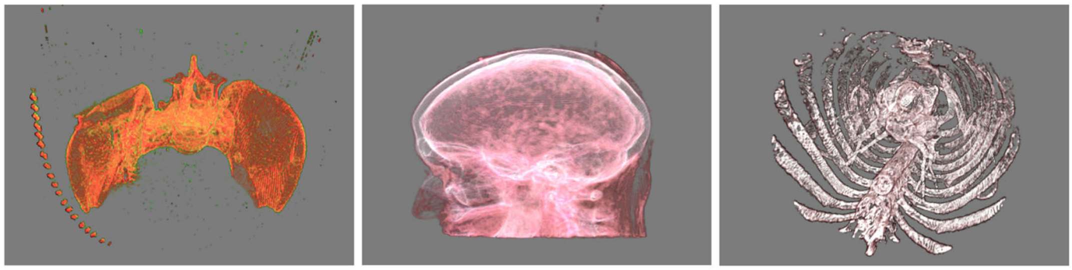

Fig. 2 Test volumes 0, 1, and 2

values. This allows the user to make more precise changes in the transfer function without the need to entirely redesign the function.

4 Usability studies

User tests with laypeople and informal interviews with professionals were conducted to verify if the proposed sketch-based interface is more effective and efficient, when compared to conventional WIMP approaches. As for the user tests, performance metrics such as time of task completion and number of attempts were considered, whereas qualitative feedback was collected through questionnaires filled out after task completion. Professional feedback was acquired from radiologists, surgeons, biomedical engineers, and science illustrators that tested Voxel TIPs. Each professional then provided several comments and a list of pros and cons of the proposed interface

4.1 User tests with laypeople

A total of 15 unpaid participants with ages between 19 and 24 years (21.8 ± 1.7 years old), 5 of which women, were asked to design transfer functions that would closely reproduce a set of volume rendering imagery. All participants were college students enrolled in Engineering courses (Bachelor or Master), and used interactive surface technology (e.g., smartphones or tablets) several times a day (> 5 times a day).

Voxel TIPs was compared to VoTracer, an interface that faithfully follows the WIMP approach. When using Voxel TIPs, participants were required to stand in front of the tabletop using one or both hands. When using VoTracer, the user was seated in front of a computer display and inputted data via mouse controls to perform both design and navigation tasks. Three different Computed Tomography volume data sets (available at the OsiriX image data base) were used for each test: fractured pelvis bone (Test 0—PELVIX) was used as a training volume for user habituation, while brain tumor (Test 1—BRAINIX) and lung carcinoma (Test 2—CARCINOMIX) volumes were used to measure task performance (Fig. 2). The test sessions were individual and each task was timed. The expected duration of a test session was about 25 min and was divided in two phases. At the beginning of each phase, a short system presentation was made in order to explain how each objectified functionality worked. Afterward, the user would test the systems up to 5 min to achieve habituation. During each phase, either Voxel TIPs or VoTracer were tested and the user performed three transfer function design tasks. Finally, to assess the level of difficulty felt during their tasks performance and on the use of the available features, users were asked to complete a questionnaire regarding the system and the performed tasks.

Before each test, the tasks and interfaces were randomly sorted, as balanced as possible, among the number of users per initial system in order to avoid biased results. At the beginning of Test 1 and Test 2, a volume rendering image was presented to the participant, which was then asked to obtain a similar image by sketching the transfer function. Each task was timed and the number of attempts was determined. Here, an attempt was considered every time the user performed one of the following actions: (1) have reset the function to its original state; (2) have reverted the function to a previous form; and (3) sketched a function that was not intended.

By default, participants start each test with all terms of the transfer function initialized at full opacity. Afterward, and for both design approaches, each test followed a sequence of design tasks. The first and second tasks required the definition of the intensity-based and gradient-based 1D transfer functions, respectively.

Within VoTracer, the participant sketched intensity-based and gradient-based transfer functions directly over the canvas by using the mouse pointer. Contrary to WIMP approaches, Voxel TIPs allowed participants to sketch initial concepts for intensity-based and gradient-based terms by applying a sliding window, which is used to scan the intensity and gradient magnitude domains, followed by configuring multiple sliders to assign nonzero opacity values to the region of interest. The participant could then manually fine tune the function via free-form sketching.

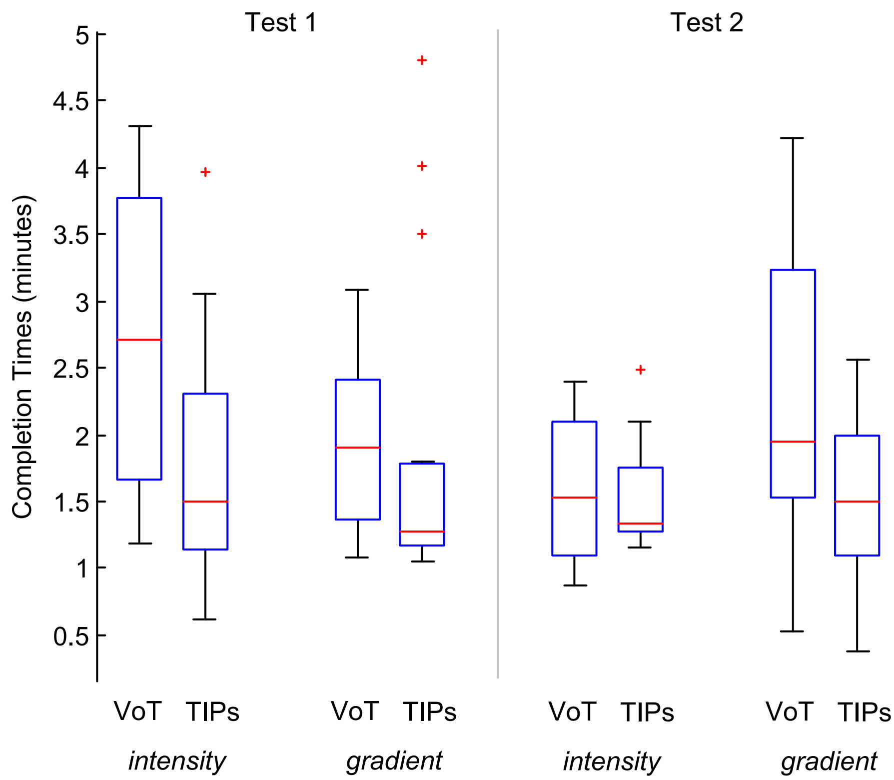

Fig. 3 Design completion times of intensity and gradient magnitude transfer functions using VoTracer (VoT) and Voxel TIPs (TIPs) for Test Volumes 1 and 2

4.2 User evaluation with healthcare professionals

In order to obtain feedback on Voxel TIPs medical usefulness, the proposed interfaces was presented to a general surgeon and two radiologists from the Hospital Professor Doutor Fernando Fonseca (E.P.E.). The senior surgeon and one radiologist had a very positive reaction when presented to this interface. They considered that Voxel TIPs had great potential as a tool to highlight structures of interest based on intensity, namely the visualization of deformed structures that appear in neurogenic bladder dysfunction, which are hard to recognize even for those specialized in radiology. Both radiologists considered that Voxel TIPs is suitable for both educational and museological purposes. Such an application would allow medical students to both study anatomical structures under pathological conditions and to understand how they relate, which is often difficult to achieve with the conventional approaches. Regarding diagnosis, both radiologists was more conservative as they considered Voxel TIPs to be more suitable to produce medical illustrations rather than to contribute for an efficient radiodiagnostic, as radiologists do not have much time available for image post-processing.

4.3 User evaluation with scientific illustrators

After collecting feedback from healthcare professionals, we performed informal interviews with two senior scientific illustrators to access its potential in illustration. Both professionals pointed out that Voxel TIPs could be very useful when combined with image edition and 3D modeling software tools. Moreover, they also considered that thumbnails added a great graphical value to the design approach. However, it was suggested that a short tutorial was missing to better understand the concept of 1D histograms, yet this is out of the scope of this work [3]. Most importantly, the illustrators considered that the design process supports the creation of images that are a good starting point for the illustration pipeline, which can be used for inspiration and further edition in more specialized software.

5 Results and discussion

In order to evaluate users performance, the completion time (Fig. 3) and number of attempts for each transfer function design task (Table 1) were measured and compared to determine in which interface users achieved the desired result in the least amount of time.

Users were able to design appropriate transfer functions in both systems, and they rapidly understood how to interact with the sketch-based interface as they easily completed each task, without ever having used a transfer function design tool before. However, Voxel TIPs revealed to take lesser time and smaller variance for designing intensity- and gradient-based functions. The average completion times for both test volumes were shorter using Voxel TIPs than when using

Table 1 Evaluation times and number of attempts of the transfer design tasks using VoTracer (VoT) and Voxel TIPs (TIPs) for Test Volumes 1 and 2

		Test 1				Test 2			
		Intensity		Gradient		Intensity		Gradient	
		VoT	TIPs	VoT	TIPs	VoT	TIPs	VoT	TIPs
Completion times (minutes)	μ	2.9844	1.75	2.1522	1.8556	2.0944	1.4734	1.9733	1.5178
	σ	1.7911	0.9672	1.1887	1.2094	0.9788	0.9373	1.3452	0.4095
	p	0.0285*		0.5036		0.227		0.0559	
Number of attempts	m	9	1	7	3	7	3	6	4
	IQR	6.75	2.50	4.00	1.00	9.25	1.00	7.75	3.25
	p	0.0017*		0.0049*		0.0325*		0.0702	

*Indicates statistical significance. (μ: mean; σ: standard deviation; m: median; *IQR*: inter-quartile range; p–p value)

VoTracer (Table 1). This can be explained by the fact that Voxel TIPs allows the user to sketch the function directly using his/her finger tips, and from the ease of sketching the transfer function directly without the aid of a drawing device. The paired t test ($p < 0.05$) reveals that the tasks performed with Voxel TIPs were substantially faster than VoTracer (Table 1). Interestingly, the gradient-based design in Voxel TIPs presents the smallest time completion variance when compared to VoTracer or with intensity-based design.

(Table 1) also lists the statistics for the number of trial-and-error attempts to obtain the desired transfer function. The number of attempts is significantly smaller when using Voxel TIPs comparatively to VoTracer, which in part explains the smaller average completion times using Voxel TIPs.

After performing the tasks, users were asked to answer two surveys. To obtain an overall opinion of user's preferences, the first survey presents a Likert-type scale for rating questionnaire responses related to transfer function design performed in WIMP and sketch-based interfaces (Table 2). When asked about the overall level of difficulty felt when designing the transfer function, users found it more difficult to sketch a function with a mouse, preferring touch gestures that more accurately reproduce the users intentions to sketch transfer functions.

A second survey was carried out to attend users preferences regarding the novel sketch-based tools. A binary response scale screening questionnaire [5] was considered. Users preferred the use Voxel TIPs for both intensity-based (87%) and gradient-based (93%) function design over the conventional mouse approach. Users slightly preferred the use of the sliding window (intensity: 53%; gradient: 60%) over the mixing table (intensity: 47%; gradient: 40%) as the first tool to find an initial approximation of both transfer functions. Curiously, most users responded that they did not immediately obtain the expect result when sketching the transfer functions either with a mouse or with touch gestures.

Noticeably, users referred that thumbnails not only act as important visual aids, which allowed for an overall view of

Table 2 Participants preferences regarding different criteria for the evaluated systems: Median (inter-quartile range). Likert scale: 1—totally disagree and 4—totally agree

How easy was it to …	VoTracer	Voxel TIPs
Generally use the system?*	2 (1)	4 (0)
Perform Test 1 (intensity)?*	3 (1)	4 (1)
Perform Test 2 (intensity)?*	3 (0.75)	4 (0.75)
Perform Test 1 (gradient)?	3 (1)	3 (1)
Perform Test 2 (gradient)?*	2 (1)	4 (1)
Understanding the mapping between voxel intensity and intensity-based transparency?*	3 (1)	4 (1)
Understanding the mapping between voxel intensity and gradient-based transparency?	3 (1)	3 (1)

*Indicates statistical significance

the volume content, but also complemented the design tasks. For instance, thumbnails helped users to decide which intensity intervals should contribute to the final volume rendering image. By combining histograms to thumbnails, we explored the "DJ mixing table" metaphor for adjusting how much of intensity interval will contribute to the overall transfer function. Thumbnails enable an easy and quick reading of the volume data domain. This becomes more apparent by comparing the performance of the gradient-based design with the intensity-based design, which was slower despite having all the same tools except for the presence of the thumbnails.

Note that all sketch-based tools focus interaction to specific intervals of the data domain, resulting in a more methodical interaction experience. This contributes to reduce the number of attempts related to trial-and-error design iterations, making transfer function design a lesser iterative approach and more a step by step procedure. This is not the case with conventional WIMP approaches, where users directly jump into drawing the final transfer design without properly scouting the data domain, resulting in a higher number of attempts and much greater variability of the results.

The set of sketch-based tools allowed a rapid inspection of the volume intensity distribution, enabled users to directly sketch the function throughout the entire domain and to add details using touch gestures. In addition, such tools promoted a better understanding of the mapping between data values and opacity, and hence, between intensities and anatomical structures.

However, the lack of significant results when designing the gradient transfer function may indicate that users still have noticeable difficulties understanding the function domain or histogram information. 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.

By testing the adequacy of a sketch-based interface to explicitly draw transfer functions when compared to the standard interface, the user study results confirm that the proposed sketch-based interface consists of a useful combination of transfer function design techniques for practical volume visualization applications. Our work addresses a present-day issue as current software packages (e.g., volview, voreen, exposure render, inviwo) still remain faithful to mouse-based transfer function design. On the other hand, several studies have considered sketch-based interaction, but none were tailored for explicit transfer function edition.

Overall, we presented a balanced combination of histogram views, thumbnails and sketch-based tools. The resulting interface offers domain experts the ability to perform both global and local customization of transfer functions, to quickly deliver an initial design and yield several alternative volume-rendered images for rapid communication. In addition, the proposed sketch-based tools can easily be integrated into existing rendering systems, does not rely on complex mathematical formulations, users can globally define transfer functions by applying different types of function shapes not just trapezoids or further add intricate details using freeform sketching.

6 Conclusions and future work

Designing appropriate opacity and color mappings with conventional WIMP approaches can be a difficult and tedious process. In this work, a sketch-based interface for transfer function design using a direct control approach was developed and interaction methods were proposed to rapidly design 1D transfer functions. Through a usability study we compared the proposed spatial interaction system with a conventional WIMP system. Users are able to sketch intensity-based and gradient-based transfer functions on an interactive surface. Comparatively to WIMP approaches, designing transfer functions on a sketch-based interface takes less time and reduces the number of attempts necessary to obtain a desirable function. The sketching nature of the interface enabled the exploration of novel interactive techniques to aid transfer function design, namely, sliding window and multiple sliders. Both techniques promote increased understanding of the relationship between intensity or gradient value distribution and corresponding anatomical structures. We also presented a simple and viable design metaphor where a user can initiate his/her design process by rapidly building the drawing foundation for a more meaningful transfer function using a DJ mixing table.

Explicit transfer function design is a challenging task since the vast majority of users are not familiar with concepts such as mapping of optical properties (e.g., color and opacity) from values in the data domain. Therefore, a possible future work would consist on extending the interaction model developed by [10] to support sketching tools as those presented in our work. Besides performing volume editing by selecting or removing structures and regions on histogram views, if the user could sketch the transfer function on top of the histogram view, this would lead to more interesting visualizations as it would combine voxel selection/removal with voxel transparency editing.

Other possible future work consists of extending the sketch-based interface to include more sophisticated transfer function design tools to support higher dimensions. For example, to map the opacity values to each intensity-gradient pair, we can consider a sketchpad with an underlying 2D histogram, where users could sketch a 2D patch and a thumbnail would be automatically generated. The same options available to design 1D transfer functions can be used, as well as the domain inspection tools which aim at reducing the trial and error in the design of the desired function. The 1D transfer functions could be placed at the bottom and left side of the 2D domain so that the user could better draw or delete the patch of interest. Over the sketchpad, users could draw arbitrary patches (or closed curves) to define or delete specific segments within the 2D domain. Points outside the selection patch are set to have zero opacity. The user could manually select an area by drawing the perimeter of the desired patch. Whenever opacity values needed to be settled, the flat 2D histogram view would become a 3D plot where users could rotate the plot and then select the 2D patch and raise/lower the transparency height.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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