InShape: In-Situ Shape-based Interactive Multiple-View Exploration of Diffusion MRI Visualizations

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Abstract. We present InShape, an in-situ shape-based multiple-view selection interface for interactive exploration of dense tube-based diffusion magnetic resonance imaging (DMRI) visualizations. An optimal experience in such exploration demands concentration on the tract of interest (TOI). InShape facilitates such workflow by leveraging three design principles: shape-enabled precise selection, in-the-flow multi-view comparison, and sculpture-based removal. Results of a pilot study suggested that participants had the best interaction experience when the widget shapes matched the targeted selection tubes. We also found that widget design without losing the flow of operations facilitates focused control. Finally, quick sculpture helped reach the target selection tubes quickly. The contributions of this work are the design principles, together with discussions of usability considerations in interactive exploration in dense 3D DMRI environments.

1 Introduction

The three-dimensional (3D) tractography of diffusion magnetic resonance imaging (DMRI) usually produces a set of integral curves. When the curves are visualized with tubes constructed from a large DMRI volume, the display can become so cluttered as to impede insights into the data. Tasks such as this require selection and comparative visualizations. Various approaches exist for selection with DMRI visualizations, from intuitive 3D interaction (e.g., box selection in BrainApp [1]) and pen-based input (e.g., brush-based interface in CINCH [2]) to the use of two-dimensional (2D) embedding [3] and projection [4].

We found at least three difficulties with the current interaction techniques. The regular box shape was not precise enough for tube selection when the tubes were dense with high curvature. A second problem was related to regions designated to restrict the output to tracts of interest (TOI). When tubes were occluded, it would be more intuitive to remove the unnecessary ones than merely to select the TOIs. Existing 2D embedding methods, though addressed this occlusion problem and permitted constrained selection,

suffered from the lack of intuitive domain interpretation on the 2D plane. The 2D embedding is often not anatomically meaningful and users must switch between the 3D and 2D views to make selections.

Multiple-view interfaces enable comparative visualizations in medical imaging studies, since investigation of a dense and unfamiliar dataset can be enhanced by comparing it to other better-studied datasets [5]. Brain researchers also frequently use comparison to study abnormal or normal cases, for example, in comparing brain development of an agenesis patient (ACC) with undeveloped corpus callosum (CC). ACC is a rare developmental anomaly; the patient in this case displayed a complete absence of CC. The brain scientists postulate that the number of tubes in other areas of the diseased brain (e.g., transverse pontine tubes) may increase to compensate for the loss of CC, and they are interested in knowing where and in what ways the two brain regions differ.

With these points in mind, we have designed InShape, an interactive DMRI visualization tool to allow multiple datasets comparison and precise selection. We call the present tool InShape to stress the in-situ, shape-driven, and shape sculpture design of its DMRI visualization interactions (Fig. 1). In this work, both boxes and spheres are used for selection. We hypothesize that when the widget shape matches the target selection shape, more precise selection will be possible. To allow comparison of multiple datasets, we design the multiple-view interface to minimize the cost of switching attention between views. We also hypothesize that concentrating on a specific TOI is crucial in examining a DMRI model. Our third hypothesis is that a sculpture-based method will complement to the conventional pure-selection based method. The main contributions of this paper are the above three design principles, the InShape interaction tool for DMRI visualizations, and the pilot study results on the effectiveness of such methods.
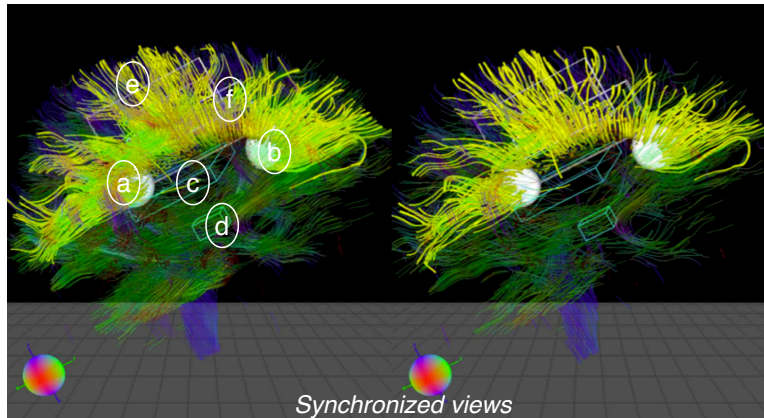
Fig. 1. The InShape interface uses widgets in two shapes: the conventional boxes and our spheres. The sphere shape can improve the user experience by allowing precise selection of regions of high curvature (a and b). In this example, two NOR boxes are colored in blue (c and d). Here selected tubes are within the white-colored boxes (e and f) and spheres (a and b) using boolean logics (a OR b OR e OR f NOR c NOR d). The corpus callosum (yellow) is selected in both views.

2   Related Work

2.1   TOI Section in MRI Visualizations

One class of TOI selection tools uses direct operations in 3D, including those using box-shaped selectors and pen-based inputs. Sherbondy et al. design box widgets to define TOIs on which dynamic queries are constructed to locate specific structures in neural pathways [6]. Blaas et al. propose a geometry-based approach for selection that uses multiple convex objects to yield reproducible bundles [7]. Their multi-box method is efficient in selecting major or regular bundles but less so for bundles consisting of jagged tubes because of the imperfect tractography often seen in practice. Brushes and strokes have also been applied to 3D selection. CINCH allows selection of 3D pathways using pen strokes [2]; in this pen-based interface, TOIs are defined by arbitrary marks drawn by a trackball. Our design facilitates desktop interaction using a mouse as input hopefully to achieve the same performance as those 3D input techniques.

Another class combines 3D and 2D views of a same dataset in interactive visualizations [4, 3]. Both Chen et al. [3] and Jianu et al. [4] use a compound interface that integrates a 2D embedding to assist in 3D exploration; here the user can select embedded points on a 2D plane in order to specify the corresponding 3D tubes. Recently, Nowinski et al. present techniques for controlling system states, such as tract labeling, coloring, counting, smoothing, and thresholding [8].

2.2   Multiple-view Visualizations

A common approach to concurrent exploration of multiple datasets is to use multiple views. It is useful to overlay different visual representations in one viewport in order to enhance and clarify visualizations [9, **?**]. Multiple views have been used, especially in information visualization, to support simultaneous explorations of multiple models [10]. One powerful approach to coordinating views is brushing-and-linking, an exploratory data-analysis technique for displaying a set of data items in multiple views [11]. Items selected by the user in one view are automatically highlighted in other views. For example, the well-known tool Polaris uses brushing and linking with a rubber-band lassoing tool [12].

Keefe et al. employ a multi-view strategy for biomechanics data visualization, making a view of small multiples, a 3D inspection view and parallel coordinates view work together to support a motion sequence data analysis [13]. VisTrail presents the visualization of a set of different instances of time-varying data in multiple views, each view showing one instance [14]. The workflow framework supports multiple visualizations generated from different pipelines as well.

Both 2D and 3D views can be displayed for exploratory data analysis [4, 3]. The 2D view can also complement the 3D view by providing contexts for navigation in complex geometries or for interpretation of the actions performed in the 3D view. With a visualization technique called multiple-scale small multiples, Chen et al. use multiple views for dynamic displays of bat-flight kinematics models that give users multiple levels of details and scales of the dataset [15]. In our implementation, we focus on reducing the cost of switching context between views in the widget interface design.

2.3   Removal-based Method

Removal-based methods have previously been employed for 3D explorations. Interactively sculpting 3D objects by moving voxel-based tools within a model is used as a modeling technique [16]. This reverse approach has also been applied to interactive volume editing, called volume sculpting [17]. Multi-resolution volume sculpting is also made possible in [18]. In this work, we expand the literature to apply the sculpture-based method to DMRI visualizations.

3   Methods

3.1   Shape-driven Selection

In clinical tasks using DMRI visualizations, brain researchers usually want to make accurate investigation of certain tube bundles. But due to the irregular shapes of DMRI tubes, they often find exact bundle selection very difficult. In a brain DMRI tube model, some bundles, like those in the stem region, fit a box-shaped selection very well, but efficient and precise selection of others, like those in the genu or splenium part of the corpus callosum, is best done by a sphere-shaped selector due to their curvilinear nature (Fig. 2).

(a) Using two boxes   (b) Using two spheres
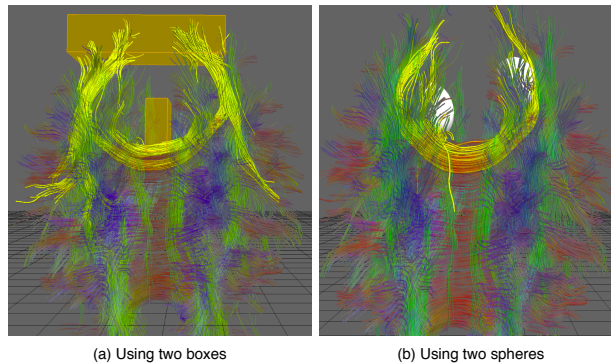
Fig. 2. Genu selection. The two spheres in (b) can select the tracts more precisely compared to the boxes in (a).

In contrast to the box-shaped selectors in many existing TOI interface, spheres are designed in InShape because their curvilinear shape can make them a better fit in selecting curvilinear tubes than the regular shape of boxes. For example, selecting the CC genu tubes would require at least two selection boxes and the rectangular corners of the boxes would inevitably include undesirable tubes. In comparison, a single properly placed sphere can perform the selection precisely and quickly. In addition, boxes are more visually demanding during interaction because of their many operational faces and thus less desirable to brain researchers than spheres that operate in one dimension only.

Nevertheless, InShape retains box-shaped selectors in order to select approximately regular tubes such as those in the brain-stem regions. Emphatically, InShape features shape-driven TOI selection by which proper selector type can be chosen according to the shape of target TOIs. They can be used together in tasks in which target TOIs include both regular and curvilinear tubes (such as that shown in Fig. 1).

3.2 *In-the-flow* Multiple-view Visualization

Brain researchers often want to examine multiple DMRI models side-by-side so as, for instance, to recognize brain anomalies in a suspect model by comparing it to a normal brain model or to observe disease development over time using images of a same person. In response, multiple views are used in InShape to support multiple comparisons. A known difficulty in multiple-view design is the context switching, necessitated when users look at different portions of the views: this attention shift can derail them from the current workflow. The context-switching problem can be worsened in dense DMRI datasets where a slight modification can cause a complete change in the selection results.

A guiding principle in our design is that all interaction should be performed within the context of the model. One approach we use is to design the hover-over widgets for making selections in place (Fig. 3). Hovering over a sphere or a box widget activates the hover-over widgets. An entire set of operations can be involved, such as resizing widgets, alternating selector behavior, changing associative logic among selectors, and cloning or deleting the selector (Fig. 3 (c)).
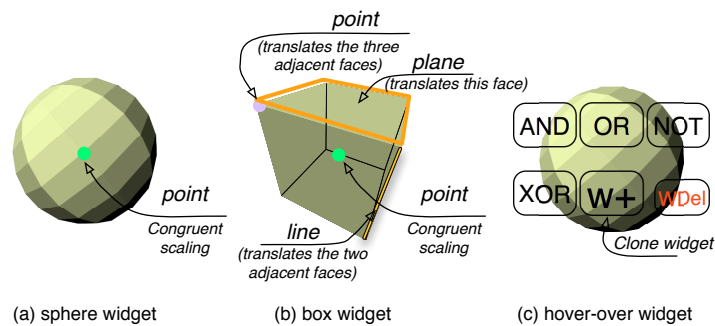
Fig. 3. A set of widgets appears on a box or sphere when the mouse cursor hovers over the box or sphere widget.

A sphere can be resized through congruent scaling by left-dragging, moved on the viewing plane by right-dragging around the sphere center, and moved along the depth dimension by right-dragging the sphere boundary. Similar work modes are applicable with the box-shaped selectors. A box can be resized by left-dragging any of its front-facing faces or the vertices or edges on them. In addition, congruent scaling by right-dragging around the center of a front-facing face is also available for quicker resizing,

while right-dragging the eccentric area of the face is mapped to panning. Users can also move a box along the depth dimension, as is necessary in exploring a 3D visualization, by right-dragging an edge of a front-facing face.

As in other multiple-view systems, the actions are synchronized in views. Rotating in one view can induce simultaneous rotation in other views. Selection and sculpting are also synchronized. When the user operates in any of the views, all interactions with mouse inputs are mirrored in all other views. This synchronized-actions mechanism can be useful in comparing datasets, e.g., a patient's DMRI captured at different times. The multiple-view interface is also useful when combined with sculpting. In the case where a normal brain is to be compared with one with ACC, for instance, the doctor used InShape to put the two datasets side by side, cull the peripheral tube bundles using the sculpting, and then fully engage in the tube bundles around CC; the doctor was able to confirm an hypothesis using our visualization with the InShape interface.

3.3   Sculpture-based Exploration

Brain researchers would like to quickly sculpt away pathways not relevant to their tasks. They comment that their tasks are often related to a small region of a brain that might be too deep and therefore they would like to sculpt out TOIs from dense tubes so the inside can be seen. Fig. 4 illustrates a task scenario where a brain researcher can examine the corticospinal tracts and the corpus callosum areas. He or she starts with a whole-brain DMRI tube model and uses a sculpting sphere to gradually sculpt away the peripheral tubes irrelevant to the current task to expose the two tube bundles for further interaction. The user can rotate, zoom, or pan the dataset during in the sculpting process.

(a) whole brain tractography   (b) fibers after sculpting away peripheral fibers
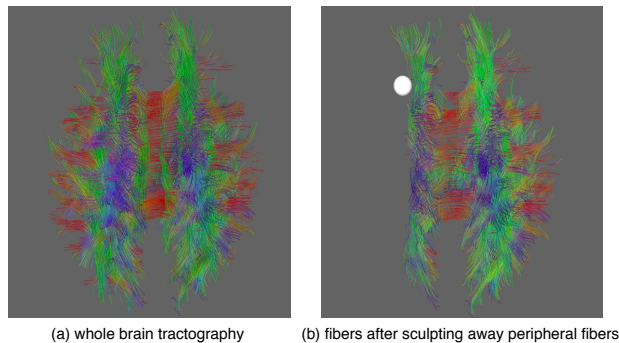
Fig. 4. Sculpture-based interaction.

The sculpture widget (a box or a sphere) excludes undesirable tubes that would otherwise occlude the view. This sculpture action is continuous when the left-mouse button is hold, resembling an eraser or a sculpting approach in that all tubes touched by the widget are removed. Sculpting can be particularly useful when the selection targets are known and are located in the inner regions. In addition, this action differs from the

"NOR" operator in the widget interface in Section 3.4 because of the different operation modality and results: this widget operates alone and can erase currently selected tubes. Users can simply remove those tubes that are blocking their views. Sculpting can be handy in removing large chunks of irrelevant tubes and helping the brain researchers reach their tracts of interest.

3.4   User Interface

Our interface also supports associative logics, such as those in BrownApp [1], CINCH [2], and [19]. The sphere or box can work in either the "ADD" or "OR" or "NOR" mode. Table 1 shows InShape selector behaviors in each mode. Fig. 5 demonstrates the results from the multiple-widget interaction.

Table 1. *A*ssociative logic among multiple selectors

associative relation	selector behavior
AND	Tubes passing all selectors are selected
OR	Tubes passing one or more selectors are selected
NOR	Tubes passing all selectors are removed

(a) a AND b   (b) a OR b   (a) b NOT a
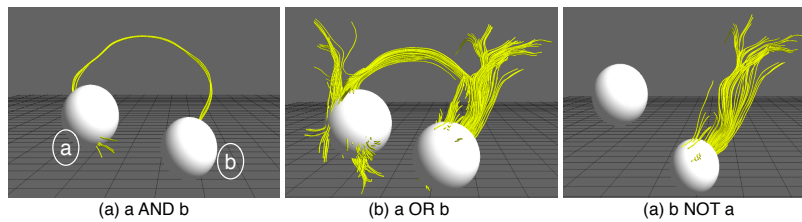
Fig. 5. Boolean logic operators.

4   User Evaluation

In order to verify the usability and effectiveness of our InShape interface, we invited two participant groups to test the tool. We hypothesized that the sculpting interface empowered by the shape-driven design and multiple synchronized views would enhance users' efficiency and accuracy of TOI selections. Our goal was to check whether users perceived value in the mixed selectors, removal-based design, hover-over widgets, and the intuitiveness of the user interface. The DMRI experts included a radiology professor and two medical students, and the non-DMRI group contained two computer science students. None of the non-DMRI group had experience in computer-based DMRI exploration.

4.1   Tasks

The participants were allowed to explore the data freely. They were also asked to select the white-matter bundles of their personal interest using InShape. A think-aloud protocol was enforced. With the non-DMRI group, it was our intent to collect data on the usability issues of the interface design. The tasks were replicated from an earlier study [3] for selecting a set of tube bundles: corpus callosum, bilateral cingulate bundles, corticospinal tracts, superior longitudinal fasciculus, and cingulum and uncinate fasciculus, selected by our brain scientist collaborator with expert knowledge of white matter anatomy. Since this non-expert group of participants did not know DMRI tractography, we highlighted these bundles in yellow. Both the single-view and dual-view conditions were tested, with one view showing a normal dataset and the other view an ACC dataset.

4.2   Dataset

Two tube models of human brains were used in the study: a normal brain model in voxel resolution $0.9375mm \times 0.9375mm \times 4.52mm$ and a diseased model (agenesis) in resolution $1.71875mm \times 1.71875mm \times 3.00mm$. Whole brain DMRI tractography was performed using streamline tracing and culling techniques [1]. The normal case had 9,635 tubes and the agenesis case had 8,379 tubes.

4.3   Procedure

The experiment began with training in the concept of DMRI and the functionality of the InShape interface. Participants were asked to practice until they felt comfortable using InShape. The experiment for the three-expert group lasted about 2.5 hours and that for the other group about an hour.

We collected task completion times and measured selection accuracy, defined by bounding tightness (false positive, indicating how many non-TOI tubes are selected) and tube coverage (false negative, indicating how many TOI tubes that should not be selected are selected). Computer-based log data were collected to record all participant actions such as mouse click, rotation, selection, zoom, and drop-down menu use.

5   Results and Discussion

In general, participants found that the interface was useful in examining the white-matter pathways and anatomical structures in the brain, and helpful in making accurate tube selections. The non-DMRI group performed more quickly than the DMRI group but the sample is too small to determine if the difference is statistically significant. The average task completion time was 2.2 minutes for the non-DMRI participants with relatively high selection accuracy, but we must interpret this result carefully in comparison to other tools in experiments with different sampling population, sample size, and test settings.

Participants were inclined to use 1D input with the box widget. Our log data showed that the participants mostly tended to resize the box using 1D face movement ($> 30\%$),

perhaps due to its low movement cost. Participants do not have to modify two or more planes simultaneously when a higher-dimensional manipulation is activated.

Participants also reported that the sphere shapes made selection easier and the scene less occluded. DMRI expert participants suggested several other extensions. One participant suggested situating a sphere widget in polar coordinates, so that the selection can be made by placing the center of the sphere within the TOI; coupling this method with the sculpting could make the initial selection more efficient. Increasing the size of the sphere would enlarge the selection context to show more tubes of interest. This implies that loading a good initial default (such as a sub-volume of the brain) could further simplify TOI selection.

The removal mode was reported to be effective and the sculpting approach was judged a good fit to the way brain researchers examine brain models in practical tasks. Additionally, the shape-driven design was considered useful because using boxes for TOIs of regular shape and spheres for those of curvilinear shape enhances selection accuracy. Participants also appreciated the in-the-flow interaction since it let them focus fully on their TOIs. While the multiple-view synchronization helps comparative study of multiple brain models, matching anatomical regions among brains (rather than merely calibrating on the geometry level, as currently) would be more helpful. As expected, the participants reported that they did not need to look away from the models with the hover-over widget. A brain scientist also commented that a tool as such could be useful for scientists interested in understanding the structural and functional correlates of brain circuitry and for understanding the regional impact of disease or injury on the brain.

6   Conclusion

We have presented InShape, an in-situ interface for interactive exploration of dense DMRI tubes. InShape extends many well-known techniques (box-based selection and brush-and-linking) to allow precise selection with spheres and sculpting away tubes within the model context. It also presents a prototype of shape-widgets, sculpting-based interaction, and multiple synchronized views for more precise selection. A formal study with more brain experts is planned to compare our interface with the 2D separated views in order to learn if our interface helps reduce the cognitive barriers between examining in 3D while selecting in 2D. We are also interested in comparing the shape style of selection and removal against more common methods like brushing and box selection in speed, comprehension, and user experience in general.

Acknowledgment

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