Composing DTI Visualizations with End-user Programming

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Abstract

We present the design and prototype implementation of a scientific visualization language called ZIFAZAH for composing 3D visualizations of diffusion tensor magnetic resonance imaging (DT-MRI or DTI) data. Unlike existing tools allowing flexible customization of data visualizations that are programmer-oriented, we focus on domain scientists as end users in order to enable them to freely compose visualizations of their scientific data set. We analyzed end-user descriptions extracted from interviews with neurologists and physicians conducting clinical practices using DTI about how they would build and use DTI visualizations to collect syntax and semantics for the language design, and have discovered the elements and structure of the proposed language. ZIFAZAH makes use of the initial set of lexical terms and semantics to provide a declarative language in the spirit of intuitive syntax and usage. This work contributes three, among others, main design principles for scientific visualization language design as well as a practice of such language for DTI visualization with ZIFAZAH. First, ZIFAZAH incorporates visual symbolic mapping based on color, size and shape, which is a sub-set of Bertin’s taxonomy migrated to scientific visualizations. Second, ZIFAZAH is defined as a spatial language whereby lexical representation of spatial relationship for 3D object visualization and manipulations, which is characteristic of scientific data, can be programmed. Third, built on top of Bertin’s semiology, flexible data encoding specifically for scientific visualizations is integrated in our language in order to allow end users to achieve optimal visual composition at their best. Along with sample scripts representative of our language design features, some new DTI visualizations as the running results created by end users using the novel visualization language have also been presented.

Keywords: End-user programming, visual language design, scientific visualization, DTI

Index Terms: H.5.2 [User Interfaces]: Programming Language—; I.3.6 [Methodology and Techniques]: Languages—

1 Introduction

Visualization tools often support user customization, which allows changes of the visualization so as to help users gain better understanding of the underlying data to facilitate knowledge discoveries about the data that would be hard to achieve otherwise. However, the support of user creativity is usually constrained by the limits of predefined options or functionalities for the customizations.

An effective way to address these constraints is to offer users a programming environment in which they can freely compose towards desirable visualizations of their data through a visualization language. While such languages have been proposed and successful in the information visualization (InfoVis) community [17][25][12], there is a lack of end-user visualization language for 3D scientific visualization (SciVis). Based on our many discussions with domain users, we have recognized that domain scientists want a visualization of their own data to be designed and built by themselves. Now that the success of visualization languages for InfoVis is probably attributed to their capabilities of empowering users to design their own visualizations, what if domain scientists have a visualization tool that is powerful but easy to maneuver so that they can fully control the design elements and visual components to create whatever visualization they really want in mind?

A recent advanced MRI technique, diffusion tensor imaging (DTI) has proven advantageous over other imaging techniques in that it enables in vivo investigation of biological tissues and, through three-dimensional (3D) tractography [8], explorations of the distribution and connectivity of neural pathways in fibrous tissues like brain whiter matter and muscles. Further, as one way to visualize DTI data, 3D visualization of the streamline data model derived from the tractography can illustrate the connectivity of fiber tracts and structures of anatomy, and therefore provides a powerful means that assists neuroscientists in clinical diagnosis and neurosurgical planning.

We proposed a visualization language as the first tool of this kind for DTI visualizations because DTI is complex enough to stimulate a design that would be useful for simpler and similar visualization problems such as that of flow visualization. Although mainly driven by neurologists’ need for conducting their clinical tasks with DTI visualizations, our language design would also be reusable in a broader range in 3D SciVis. Motivated by the needs of spatial explorations in 3D scientific visualizations because of the spatial constraints within the data, the present language is particularly useful in empowering domain scientists to build 3D visualizations that best meet their specific needs.

Furthermore, the language can facilitate domain scientists’ effective use and exploration of the visualizations as well, because it allows them to customize essential elements of visualization with the maximal flexibility by applying their best understanding of the domain data to the visualization composition process. Illuminated by Bertin’s Semiology of Graphics [2], we design the language to allow users to compose symbols in 3D visualizations, including visual encoding methods and other causes that affect visualization task performance.

Figure 1: A screenshot of the ZIFAZAH programming interface, consisted of a programming text board (upper left), a simple debugging output window (bottom left) and the visualization view (right).
To capture the design elements of the language, we have conducted experimental studies with domain scientists in DTI who are expected users of our language and summarized design principles for the language out of their descriptions of visualization making and exploration, from which basic lexical terms such as verbs, prepositions and conjunctions were also reduced. With these principles and language elements, we have developed a language prototype, named ZIFAZAH, as an initial implementation of the visualization language we are proposing. To target non-programmer users like neural medical doctors, ZIFAZAH is designed to be a high-level declarative language.

Also, for an easier usage for users without any programming skills and experiences, ZIFAZAH is currently developed as a procedural language that contains only an intuitive type of control structure, i.e. the sequential structure. As such, users can write ZIFAZAH scripts simply as if they verbally describe the process of authoring visualizations in sequence. Figure 1 gives an outlook of the ZIFAZAH programming interface.

The following usage scenarios briefly show the utility of ZIFAZAH. In the first scenario, an end user first loads a whole DTI model and then programs to vary tube size in the default streamtube visualization by fractional anisotropy and tube color by fiber distance to the viewing point in a specific brain structure. In the end of his task, the user can change the streamtube representation of another brain region to ribbons.

In the second one, an user filters fibers according to an estimate of linear anisotropy threshold and then gradually adjusts the threshold until satisfied. The user then further cuts off the selected fibers outside a target brain region through spatial commands with precisely calculated movements and thus reaches the tubes of interest.

As the final example, an user can get the size of a brain structure in terms of the number of fibers, average fractional anisotropy in a brain region, and other common DTI metrics after reaching the target fibers. In each of these scenarios, the user achieves each step by writing a declarative program statement in the script editor and the results are reflected in the visualization view (see section 5).

Apart from a visualization language that helps domain scientists build DTI visualizations by themselves to exactly meet their specific needs with the visualizations, our work also contributes several design features to general DTI visualizations including: (1) visual symbolic mapping based on color, size and shape, as is new for scientific visualizations, (2) lexical representations of spatial relationships for 3D object visualization and manipulations and (3) data encoding flexibility built upon the migration of Bertin’s semiotic principles to scientific visualizations.

The following snippet gives a quick view of how a ZIFAZAH program looks like. This script describes an exploratory process of an end user with the streamtube model [32] of a human brain DTI data set, in which different fiber bundles (CC, CST, etc.) are filtered according to threshold of DTI metrics (LA, FA, etc.) and customized with various visual encoding methods (shape, color, size, etc.).

```
LOAD "/tmp/allfb_tagged.data"
SELECT "CC"
SELECT "FA in [0.2,0.25]" IN "IFO"
UPDATE color BY FA IN "CC"
UPDATE "LA > 0.35" IN "CST"
UPDATE shape BY line IN "CC"
UPDATE shape BY tube IN "IFO"
UPDATE size BY FA WITH 0.1,20 IN "IFO"
```

As shown in this example, a ZIFAZAH program is essentially an intuitive sequence of steps each carrying out a single visual transformation of data. Although the script is written in a textual form as in a traditional computer programming language, each of the statements is more like a high-level command. Also, there is no any other logic structures than the sequential one in ZIFAZAH, which makes this language fairly easy to learn and use for end users in medical field.

The rest of this paper is organized as follows. We first give general background and discuss related work in Section 2. In Section 3 we detail design principles and supporting language elements and then brief implementation issues in the following Section 4. Section 5 expands the details of the three usage scenarios introduced above and gives the corresponding ZIFAZAH scripts and running results. We discuss other design features of our language that have not yet been fully implemented but are integral to our overall language design in Section 6 before finally concluding the paper in Section 7.

2 BACKGROUND AND RELATED WORK

In this section, we describe previous work related to our visualization language design and especially compare them against ZIFAZAH.

2.1 Visualization of DTI Models

In general, DTI data set can be visualized using various approaches ranging from direct volume rendering of tensor field [21] to geometry rendering of the fiber model derived from tensor field. With geometry rendering, DTI fibers are usually depicted as streamlines [20], streamtubes and streamsurfaces [32]. In order to explore 3D visualizations of the fiber geometries, 2D embedding and multiple coordinated views [19] along with various interactive techniques [10] have been employed.

Many other powerful tools have also been developed for exploring DTI visualizations [6, 12, 13, 7, 10]. However, due to the data complexity, domain users’ needs for performing their various tasks in daily practice have not yet been fully satisfied by using those tools. To give users more flexibility, some of the visualization tools are made highly configurable by allowing a wide range of settings [31, 29]. Nevertheless, it is still challenging to design a thoroughly effective visualization tool to meet all the needs of users. For instance, although sometimes able to meet specific requirements, higher flexibility of a visualization tool may even make the tool more complex to use for domain users [22].

2.2 Composable Visualizations

Since pioneered the automatic generation of graphic representation [24], Mackinlay’s work has been extended lately into a visual analytics system armed with a set of interface commands and defaults representing the best practices of graphical design [25], upon which a commercial software Tableau was developed. In his work, the generation of visualizations was automated thanks to the application of a series of design rules and made adaptable to users with a wide range of design expertise via constrained flexibilities by those design rules. With ZIFAZAH, we also intend to provide an environment in which end users can flexibly build their own visualizations like Tableau. However, instead of targeting visual analysis in the context of two-dimensional (2D) information visualization, ZIFAZAH primarily aims at end-user visualization making and exploration with 3D scientific data such as DTI. Also, compared to the visual specifications in Tableau like those in its predecessor Polaris [10], textual programming is the main means for end users to interact with visualizations of interest in ZIFAZAH. Similar to Polaris in terms of using visual operations to build visualizations, the tool designed in [29] also assists user retrieving DTI fibers instead of querying relational database in Polaris.

As a toolkit, Protovis gives users high-level usage flexibility even programmability yet imposes constraints upon user programs through implicit rules to produce effective visualizations [12]. This tool has been evolved into its descendant named D3 [27] for a better
support of animation and interaction. ZIFAZAH shares some Protorvis features like addressing non-programmer audience and having concise and easy-to-learn grammar. However, different from Protovis that uses simple graphical primitives called marks to construct information visualizations and mainly targets web and interaction designers, ZIFAZAH targets neuroscientists instead and enables them not only to flexibly construct but effectively explore in the context of scientific visualizations exemplified by that of DTI data.

2.3 Visualization Languages

Processing [17] is more a full-blown programming language and environment than a traditional visualization tool. Built with the full Java programming language facilities, Processing integrates the underlying visual design rules to help user build beautiful yet informative visualizations with the support of interaction design. Although developed to be accessible for new users and non-programmers, Processing is more oriented to users with certain level of programming skills and might be still challenging for domain users like neuroscientists who are the primary audience we address. A sister visual programming language of Processing, Processing.js [2] also targets web developers. By contrast, ZIFAZAH is distinct in that it empowers end users to explore scientific data through intuitive syntax within a sequential structure rather than offering a full set of programming features in a traditional computer language as Processing does. Like ZIFAZAH, Impure [1] is also a programming language for data visualizations that targets non-programmers. Although supporting various data sources, this completely visual language is developed for information design and rather than for scientific visualizations.

Although a natural language like WordsEye [11] for visualizations might be appealing to ordinary users without any programming knowledge, we do not attempt the entirely descriptive nature for ZIFAZAH as WordsEye did at current stage. In terms of lexical and syntax design, ZIFAZAH is similar to Yahoo!’s Pig Latin [13], which is a new data processing language associated with Yahoo! Pig data handling environment that balances between a declarative language and a low-level procedural one. The language supports data filtering and grouping with parallelism by its map-reduce programming capability. However, this language did not handle visualizations or any form of graphical representations but focusing on ad-hoc data analysis. Also, ZIFAZAH sets it apart from Pig Latin in the target audience again since the latter mainly served software engineers.

The Protovis specification language [13] is a declarative domain-specific language (DSL) that supports specification of interactive information visualizations with animated transitions, providing an approach to composing custom views of data using graphical primitives called marks that are able encode data by dynamic properties, which is similar to the mapping of object properties to graphical representations in another InfoVis language presented by Lucas and Shieber [23]. To some extent, both languages are comparable to the Microsoft’s ongoing project Vedea aiming at a new visualization language [3] in terms of syntactic design and programming style, although its design goals are closer to that of Processing.

Also in the InfoVis domain, Trevis [3] is a programming language based on its predecessor Trevis [5], a framework used for context tree visualization and analysis. It supports composing visualizations but dedicates to the visualization of unordered trees. Another specific-purpose language is one presented in [28] that serves the composition of visualizations of mathematical concepts like those in basic algebra and calculus.

Recently Metoyer et. al. [26] report from an exploratory study a set of design implications for the design of visualization languages and toolkits. More specifically, their findings inform visualization language design through the way end users describe visualizations and their inclination to using ambiguous and relative, instead of definite and absolute, terms that can be refined later via a feedback loop provided by the language. Emphatically, their findings also disclose that end users tend to express in generally high-level semantics. During the design of our visualization language, we have benefited from these findings and actually have reflected them in the development of ZIFAZAH.

3 LANGUAGE DESIGN

In this section, we first summarize end-user descriptions on composing DTI visualizations from which design requirements and principles, as follow a summary of the language symbols and description of ZIFAZAH data model, are extracted and motivated respectively. The development of ZIFAZAH is driven by end-user requirements with DTI visualizations and the design principles are embodied in the language features of ZIFAZAH. After each of the language features, ZIFAZAH language elements that meet the feature are detailed, including related lexical terms and syntactic patterns. Instead of describing the implementation techniques, which are briefed in Section 4, this section emphasizes how the design principles and language elements address the end-user requirements.

3.1 Design Motivations

The design of ZIFAZAH is motivated by the needs of typical end users we target for composing DTI visualizations by themselves, which can be derived from their verbal descriptions about visualizations they would desire in our many interviews and discussions with them. We report just a few representative example comments of them on visualizations produced beforehand by computer scientists.

Our participants include neurologists and neural physicians, both conducting clinical diagnosis with DTI data visualizations. In a typical interview, participants are presented visualizations of a same DTI brain data set composed differently by manipulating various visual elements and the compositions are done by computer scientists, who then revise the composing process according to the comments of participants. As results, either the unsatisfactory visualizations are finally modified to meet participants’ requirements or suggestions for achieving the desirable visualizations are received if current tool is not capable of composing the desirable ones.

As an example, multiple visual mappings of depth values to size and color does not enhance the visualization of DTI model as expected. Surprisingly, "...it is misleading to have the different size" while color has already been used to discern depth, and "...would rather have it stay the same size as I spin it around.". However, visual mapping of depth to color is still preferable since "...I like it with the color. That is what I need to look at". Nevertheless, the composed coloring scheme in which color is mapped by depth might be also useful "...if determined by the principal eigen values". And, "...I think that color is a good idea but prefer color by orientation..." etc.

There is also a call for doing analysis in the composing environment ("...Also, one thing for fibers, I am looking at for analysis purposes"). Emphatically, both classes of participant unanimously "want to do the analysis over here on the same page, that will be good, too, rather than opening it up again and trying to do it... It will all come together. It will all be integrated into one...".

These observations all suggest that domain users, exemplified by the typical end users of ZIFAZAH above, potentially ask for a high-level tool allowing them to define a self-control sequence of operations that works towards a visualization precisely meeting their own specific needs. By allowing users to compose with well-designed visual elements, a programming environment can provide the capabilities for neurologists to create their own visualizations, by which our present work is justified.
Furthermore, our work with **ZIFAZAH** is substantially grounded upon the semiology of the graphic sign-system and especially the taxonomy about the properties and characteristics of retinal variables \(^9\) in terms of the syntax and semantics design for the scientific visualization language. **ZIFAZAH** incorporates a subset of the properties and characteristics that are most relevant, according to neurologists’ verbal descriptions about DTI visualizations, to the language structure and content: size variation, color variation and shape variation. For one thing, corresponding syntax terms are built into the language core as basic symbols. For another, semantics associated with these terms are designed to support composing DTI visualizations with respect to these retinal variables by allowing free manipulations of the attributes of related variables.

While the semiology and taxonomy is originally formulated to guide the design of 2D graphical representations, we extend them into the 3D graphical environment and employ in the case of DTI visualizations. Further, we expand the scope of this taxonomy particularly for 3D visualizations by including a dimension related to depth perception, called “depth separation” in our language design in addition to the legacy retinal dimension. Correspondingly, composing the depth separation is enabled through built-in support in **ZIFAZAH**. Primary visual elements such as value, transparency, color and size are employed once again but now for the purpose of the depth-dimension composition.

It is fairly noteworthy, and common as well, in participants’ verbal descriptions that spatial terms are frequently used and most of the terms related to spatial locations are relative rather than measured in precise units. That **ZIFAZAH** is designed to be a spatial language is exactly in response to the concerns of our target end users with the spatial relationship of data components in the scientific data model being visualized. The participants’ descriptions are also in accordance with the fact that spatial constraint is a defining data characteristic scientific visualization. Consequently, **ZIFAZAH** includes a set of syntactic and semantic supports for spatial operations in order to meet end-user needs for composing 3D scientific visualizations like that of DTI models.

Intending to be an initiative of an end-user programming approach to scientific visualizations, **ZIFAZAH** is designed to support an environment in which domain scientists as end users can compose highly customizable visualizations reflecting their thinking process with the graphical representations of their data set. Since **ZIFAZAH** is incubated from DTI visualizations, the language design primarily deals with DTI data. In this context, language elements of the present **ZIFAZAH** are derived from experimental study with neuroscientists using diffusion MRI data models. As a matter of fact, the symbols and syntax of current **ZIFAZAH** are extracted from verbal descriptions of neurologists using DTI about how they would create and explore DTI visualizations. As we often refer as end users, neuroscientists, neurologists and other medical experts who conduct clinical practice with DTI data and its visualizations are the primary audience our **ZIFAZAH** language targets.

### 3.2 Language Symbols

The core content of **ZIFAZAH** itself is a simple set of language symbols and keywords. End-user actions intended with DTI visualizations are triggered through five key verbs that are all complete words in natural English. Prepositions are used for targeting scope of data of interest and conjunctions for connecting statement terms. All operators used in **ZIFAZAH** are exactly the same as those used in elementary math. Specifically, \([\ ]\) serves range operator here for giving a numerical bound that is used in conditional expressions and + and − are relative (increment and decrement) operators rather than serving arithmetical operations (addition and subtraction). Several built-in routines are provided in **ZIFAZAH** for simple data statistics and analysis in DTI visualizations: \(\text{AvgFA}\) and \(\text{AvgLA}\) calculates the average FA and average LA of a scope of fibers respectively, and \(\text{NumFiber}\) stats the number of fibers in a fiber bundle. Among the reversed **ZIFAZAH** constants, the aforementioned five major fiber bundles in human brain model are included.

In these language symbols, all verbs and prepositions are directly picked up from our neurologist collaborators’ common descriptions of visualization composition and exploration in natural language. Fiber bundle constants are also suggested by them and operators, built-in routines and other constants are reduced from our requirement analysis of their verbal descriptions. As shown in the Table \(^1\) current **ZIFAZAH** implementation contains a small set of symbols. However, our language has been designed to be scalable to increase in each type of the symbols listed in terms of implementation techniques.

**Table 1**: **ZIFAZAH** language symbols and keywords

| Verbs       | LOAD, SELECT, LOCATE, UPDATE, CALCULATE |
|-------------|---------------------------------------|
| Prepositions| IN, OUT                               |
| Conjunctives| BY, WITH                              |
| Operators   | [ ], <, <=, >, >=, ==, =, +, -       |
| built-in routines | AvgFA, AvgLA, NumFiber |
| Constants   | shape, color, size, depth, FA, LA, sagittal, axial, coronal, CC, CST, CG, IPO, ILF DEFAULT, RESET |

### 3.3 Data Model and Input

To meet the design goals when targeting our domain end users, our visual language is intended to be straightforward for programming. Therefore, **ZIFAZAH** does not involve any distinction of specific data types. It does not require uses to deal with any low-level data processing procedures either. Instead, **ZIFAZAH** focuses on visual transformations in 3D visualization. As previous examples disclose, we have used a classified geometrical data model derived from DTI volumes, in which fibers are clustered in terms of brain anatomy. In our present data model as input to **ZIFAZAH**, each fiber has been manually tagged with anatomical cluster identity as one of the five major bundles. In practice, **ZIFAZAH**’s ability to recognize the constants for the major anatomical bundles depends on these cluster tags in the structure of the data model input. However, our language design is not restricted to only handling clustered data. Actually, **ZIFAZAH** is freely adaptable to an unclustered data model, although data target specification with the major bundle constants will be processed as the whole model then. Nevertheless, **ZIFAZAH**’s capability of spatial operations empowers users to explore ROIs in the unclustered data models.

In a **ZIFAZAH** program, the first step is to indicate the source of data model by giving the name of a data file. As an example, a **ZIFAZAH** data input statement is written as:

```
normalBrain = LOAD "data/normalS1.dat"
```

where the LOAD command parses the input file and creates data structures that fully describe the data model, including to identify the cluster tags. This input specification statement can also update current data model at the beginning of the visualization pipeline if it is not the first step in a **ZIFAZAH** script. The evaluation is optional and, when provided, saves the result to a variable (normalBrain here) for later references. This is not used in current version of **ZIFAZAH** but is required for exploring multiple data sets concurrently (see Section \(^6\)).
3.4 Task-driven Language

The language design of ZIFAZAH is originally driven by the visualization tasks that domain users need to perform in their ordinary clinical practices. Among others, some of their typical tasks are (1) checking integrity of neural structures of a brain as a whole, (2) examining fiber orientation in a region of interest (ROI) or fiber connectivity across ROIs, (3) comparing fiber bundle sizes between brain regions, (4) tracing the variation of DTI quantities such as FA along a group of fibers and (5) picking particular fibers according to a quantitative threshold, etc.

When using DTI visualizations, not only looking for the whole data model, neurologists are also inclined to concentrate on regional details. In the case of brain DTI visualizations, they often narrow down the view scope toward a relatively large anatomical area in the first place and then dive into a specific ROI. In other words, they tend to pay more attentions to ROIs than to the whole brain. More specifically, in the visualizations where neural pathways are depicted as streamtubes, the ROIs are usually clusters of fiber tracts called fiber bundles. For instance, at the beginning of a visualization exploration, one of our neurologist collaborators intends to look into frontal lobe fibers within the intersection of two fiber bundles, CST and CC, and ignores all other regions of the model. Further, suspicious of fibers with average FA under 0.5 for a cerebral disease with which the brain is probably afflicted, the user goes on to examine exactly the suspect fibers. Later on, the user focuses on the small fiber region to see how it differs from typical ones, in terms of orientation and DTI metrics, say.

ZIFAZAH is designed as a task-driven language to support this requirement process through high-level primitives such as SELECT and common arithmetical conditional operators including a range operator in. ZIFAZAH is mainly featured with facilities for step-by-step data filtering with these primitives. For example, suppose the user above is to explore the fibers of interest, he can write in ZIFAZAH as:

```
SELECT "FA < 0.5" IN "CST"
SELECT "FA < 0.4" IN "CC"
```

As the result, fibers in both interested bundles with average FA under 0.5 will be highlighted to help users focus on the local data being explored. On top of this, the user can customize the visualization of the filtered fibers through various visual encoding methods using the UPDATE syntax. This is particularly useful when he wants to keep the data already reached in focus before moving to explore other relevant local data in order to add more fibers into his focus area, or when he seeks for a more legible visualization of the data firstly reached. The instance below, following the same example, illustrates how a better depth perception achieved by a type of depth encoding, together with a differentiating shape encoding, are added up to the two selected fiber bundles respectively.

```
SELECT "FA < 0.5" IN "CST"
SELECT "FA < 0.4" IN "CC"
UPDATE depth BY color IN "CST"
UPDATE shape BY ribbon IN "CST"
```

This simple sequence of commands help users locate desirable fiber tracts with high accuracy while allowing flexible customization upon current visualizations. With this language, users compose intuitive steps to finish their tasks that are difficult to achieve by visual interactions. In this case, tracts of interest (TOIs) are first focused and then further differentiated for more effective exploration through improved legibility. In general, ZIFAZAH design emphasizes this task-driven process of visualization exploration, which fits the thinking process of end users with the present visualizations. Figure 2 shows the resulting visualization.

```
SELECT "LA <= 0.72" IN "ALL"
partialILF = LOCATE "FA in [0.5, 0.55]" OUT "ILF"
```

The SELECT statement will filter fibers in the whole DTI model with average anisotropy greater than 0.72 (by putting them in the contextual background) and highlight all other fibers. In comparison, the LOCATE statement will not update the visualization but pick up fibers outside the ILF bundle having average FA value in the specified range. Note that when no specific data encoding applied, different colors will be applied to ROI fibers in different major bundles in ZIFAZAH for discerning one ROI from another when there is more than one highlighted. Also, filtered fibers will still be in semi-transparency as the contextual background rather than being removed from the visualization.

3.5 Data Encoding Flexibility

According to Bertin’s semiotic taxonomy [9], graphically encoding data with key visual elements such as color, size and shape play a
critical role in the legibility of 2D graphical representations. In 3D visualizations, occlusion effect, an important factor considered in depth perception, has detrimental effects on impact on the overall legibility, and depth cue (DC) is an ordinal dimension in the design space of 3D occlusion management for the visualizations [16].

Therefore, we combined both aspects in our ZIFAZAH language design: symbolic mapping of color, size and shape for 3D graphical legibility enhancement and depth encoding, also via common visual elements such as color, size, value (amount of ink) and transparency, as depth cues for occlusion reduction in the 3D environment. As already shown in the previous example scripts, ZIFAZAH allows end users to freely customize DTI visualizations using either a single data encoding scheme alone or compound encoding scheme by flexibly combining multiple encoding methods. The latter leads to a mixed visualization as illustrated in Figure 1.

In their composing or exploratory process with DTI visualizations, users often attempt to examine more than one data focus simultaneously and would like to differentiate one focused ROI from others so that they will not get lost themselves within the multiple ROIs. There are also other occasions under which the users have difficulty in navigate along the depth dimension even in a single ROI. The data encoding flexibility in ZIFAZAH is driven by both of the two user attempts. For an example, suppose a user has composed the streamtube visualization of a brain DTI data set with default data encoding (uniform size, color and shape without depth cues) and now wants the overall encoding scheme to be different across fiber bundles. In order to achieve this effect, an example ZIFAZAH snippet can be written as follows:

```
SELECT "ALL"
UPDATE shape BY LINE IN "CST"
UPDATE size BY FA IN "CG"
UPDATE color BY FA IN "IFO"
UPDATE depth BY transparency IN "CG"
UPDATE depth BY value IN "CC"
WITH 0.2,0.8
UPDATE depth BY color IN "ILF"
```

Then, in the resulting visualization, each of the five major bundles will be visually disparate from others since all these bundles are encoded differently. Figure 3 shows the resulting visualization.

ZIFAZAH allows users to impose various data encoding schemes upon data targets. Such visualization customization is done by the UPDATE command, which always works in an immediate mode causing update in the current visualization after execution. The general UPDATE syntax pattern is:

```
UPDATE var1 BY var2
WITH para1,...,paraN IN|OUT target
```

where var1 indicates an attribute, such as shape, color, size, depth, etc., of current visualization to be modified, and var2 gives how the actual updating operation is to be performed in terms of its relation to var1. The parameter list ending the statement presents extra information the updating requires, as is specific to a particular data encoding operation. Like the target specification (optional with all commands as stated before), the BY clause and WITH clause are both optional. Table 2 lists all possible combinations of var1, var2 and associated parameter list already developed in present ZIFAZAH. In the table, “lower,upper” gives the bound of depth mapping and “minimal, scale” indicates the minimum and the scale of variation in size encoding. DEFAULT and RESET, when going with the verb UPDATE, act as a command for revoking all data filtering and data encoding operations respectively. The following script shows how to inspect the change of FA along fibers in a ROI by mapping FA value to tube size, which results in a more intuitive perception of the FA variation in that ROI.

```
UPDATE RESET
partialILF = LOCATE "FA in [0.5,0.55]"
OUT "ILF"
UPDATE size BY FA IN "partialILF"
```

### 3.6 Spatial Exploration

One of our main design goals with ZIFAZAH is to provide a language with which users are able to operate spatial structures. We found that our neurologist collaborators tend to frequently use spatial terms such as “para-sagittal”, ”in”, ”out”, ”mid-axial” and ”near coronal”, etc. in their descriptions about DTI visualizations in the 3D space. They also use a set of other general spatial terms including “above”, “under”, “on top of”, “across” and “between”, etc. like those found in Figure 6 and more domain-specific ones such as “frontal”, “posterior” and “dorsal”, etc. At present stage, ZIFAZAH only contains a subset rather than all of these spatial terms.

In such a 3D data model as that from DTI, spatial relationships between data components are one of the essential characters, which are actually typical of 3D scientific data in general. Accordingly, composing a DTI visualization necessitates the capability of using spatial operators with domain conventional terms in order to describe the process of visualization authoring. In response, ZIFAZAH supports spatial operations through two approaches combined. First of all, three visible cutting planes that help guide in the
three conventional anatomical views, namely the axial, coronal and sagittal view respectively, are integrated in the visualization view (see Figure 1). Then, flexible manipulating operations upon the three planes are built into the ZIFAZAH spatial syntax definitions. This enables end users to navigate in the dense 3D data model with a highly precise filtering capability exactly as they examine a brain model in clinical practice.

For instance, suppose the streamtube representation of a DTI model being programmed is derived using unit seeding resolution from DTI volumes with a size of $256 \times 256 \times 31$ captured at a voxel resolution of $0.9375mm \times 0.9375mm \times 4.52mm$, and suppose both the axial and coronal planes are located at their initial position so that nothing is cut along these two views. In order to examine suspect anomaly in the brain region of occipital lobe, a medical doctor attempts to filter the data model as such that approximately only this region will be kept. For this task, the corresponding ZIFAZAH script can be written as:

```
SELECT "coronal +159.25"
SELECT "axial -27.5"
```

Similarly, relative movements can be imposed on the sagittal plane as well. These simple relative operators included in ZIFAZAH in support of spatial exploration is also informed by the design implications given in [26] although mainly comes from user requirements of performing DTI visualization tasks pertaining to spatial operations. Figure 4 shows the resulting visualization.

3.7 Flat Control Structure

Our another main design goal with ZIFAZAH is to provide a declarative language environment for domain end users who have neither any programming skill and experience nor basic understanding of computer program structures. Consequently, we purposely eliminate the conditional and iteration structures from the language design of ZIFAZAH and only keep the most intuitive one, i.e. the sequential structure, since this simple structure is much more intuitive than the other two. This features ZIFAZAH with a flat control structure that is essential for achieving the design goal. Alternatively, ZIFAZAH uses high-level semantics to overcome its otherwise weakness in expressing user task requirements for lack of these two missed control structures through two approaches addressing the requirements for them.

First, requirement for an iteration structure usually stems from the needs to operate on multiple targets. Here in ZIFAZAH, operation target is a common term in all syntax patterns to indicate the scope of data to focus on. We address this requirement through enumeration and target term defaults in ZIFAZAH syntax patterns. On the one hand, with enumeration, end users simply list all targets in the target term to avoid iteration. For example, suppose a user intends to select three bundles and then to change size encoding for two of them, his ZIFAZAH script can include:

```
SELECT "CST,CC,CG"
UPDATE size BY FA IN "CST,CG"
```

As such, no iteration structure for looping through the multiple targets is needed. On the other hand, with term default, when missing a target term in single statement, "ALL" will be assumed as a default scope meaning the whole data model to be the target. This rule is applicable for all types of ZIFAZAH statement, which means that target term is optional in all ZIFAZAH syntax patterns.

Second, requirement for a conditional structure comes from users’ requests for a means to express conditional processing. For example, they often filter fibers according to FA thresholds. In ZIFAZAH, conditional expression can be flexibly embedded in a statement to avoid this structure. It has been shown in previous examples how to embed conditional expressions in SELECT statement. For syntactic simplicity, condition is expressed in UPDATE statement indirectly through variable reference as the following another example snippet shows.

```
suspendfibers = LOCATE "FA in [0.2,0.25]"
IN "CST,ILF"
UPDATE size BY FA IN "suspendfibers"
```

where LOCATE is an alternative to SELECT but it results in a storage of the fibers filtered into a variable for later reference instead of highlighting those fibers immediately as SELECT does (see Section 3 for detailed language elements). Figure 5 shows the resulting visualization.

Figure 4: Illustration of the design of ZIFAZAH as a spatial language.

Figure 5: Illustration of the flat control structure of ZIFAZAH program.
3.8 Fully Declarative Language

Since the end users of ZIFAZAH are medical experts who prefer natural descriptions to programming style of thinking according to our talks to them, elements even merely close to those in a computer programming language have been changed to be as declarative as possible. In ZIFAZAH, all types of statement are designed to be in a consistent pattern: started with a verb, followed by operations and ended by, optionally, data target specification, with optional evaluation of statement result to a variable for later reference if provided. This syntax consistency has been applied to even the data measurement statement where invocation of built-in numerical routines is involved. To measure the number of fibers in a selected bundle, for instance, instead of writing as:

```
users with ZIFAZAH write
```

```
   CALCULATE NumFibers("CST")
```

users with ZIFAZAH write

```
   CALCULATE NumFibers IN "CST"
```

In addition, all keywords in ZIFAZAH are case insensitive in order to reduce typing errors. Neuroscientists comment that these features make the language easy to learn and intuitive to use. Figure 6 shows the resulting visualization.

```
frontalmix = LOCATE "FA >= 0.35" IN "CST,CC"
CALCULATE NumFibers IN "frontalmix"
CALCULATE AvgLA IN "frontalmix"
```

After running, the script above will dump result in the output window in the ZIFAZAH programming environment as shown in Figure 1.

4 Implementation

ZIFAZAH is declarative in its general form with support of certain programming language features such as variable referencing and arithmetical and logical operations. At this early stage, the language scripts are not executed via a fully-featured interpreter or compiler but a string-parsing based translator of descriptive text to visualization pipeline components and manipulations upon them. The core of ZIFAZAH is implemented on top of the Visualization Toolkit (VTK) using C++. The rendering engine is driven by the visualization pipeline and legacy VTK components ranging from various geometry filters to data mappers. However, in order to support language features such as mixed data encoding and depth mapping in ZIFAZAH, a group of new pipeline components like those for view-dependent per-vertex depth value ordering has been extended on top of related VTK classes, and many legacy VTK components have been tailored for specific needs of visualizations in ZIFAZAH.

In particular, the core of ZIFAZAH, the script interpreter has also been implemented primarily as data filters in the VTK visualization pipeline. For instance, filtering according to thresholds of DTI metrics is developed as a set of separate VTK filters each serving a specific metric. As such, interpreting a ZIFAZAH script is to translate the text, according to defined syntax and semantics, to data transformations in the VTK pipeline. For achieving the data encoding flexibility, multiple VTK data transformation pipelines have been employed in current ZIFAZAH implementation.

Additionally, the overall programming interface is implemented using Qt for C++. For example, interactions like triggering execution of a ZIFAZAH program, serializing and deserializing the text script, etc. are all developed with Qt widgets, although the interactions with the visualization itself are handled using legacy VTK facilities with necessary extensions. Figure 1 illustrates the outlook of current ZIFAZAH programming interface. Both the code editor and "debugging" information window are of dockable widgets, which facilitate the script programming by allowing free positioning and resizing as opposed to the visualization view.

Since our language is definitely non-programmer oriented, program debugging skills are not expected of users. Consequently, instead of building a full-blown debugging environment as seen in almost all integrated development environments (IDEs), we simply use a dockable output window to prompt users all error messages caused by invalid syntax or unrecognized language symbols. We have made use of GUI utilities of Qt for C++ to dump, after running a script, those messages to tell what and where is wrong in natural language description with different levels of errors (fatal, warning and notice, etc.) differentiated by different combinations of font size, type and color of the text. Resulting values out of running data analyzing statements are also displayed in this output window. We do not set a separate window for displaying those numerical results in order to simplify the programming interface and, alternatively, we use remarkably disparate text background and underscore to highlight them among other messages. Also, natural
language description has been used to present those numerical results so that they are easy to read and understand for end users.

Although there is no special requirement regarding hardware platform configuration, a high-speed graphics card like those having, for instance, 512M VRAM and 50MHz GPU is preferred for rendering the dense 3D DTI data model efficiently, which makes the ZIFAZAH programming environment work smoothly as a whole.

5 Usage Scenarios

In this section, we describe several sample tasks done by neurologists with visualizations of a brain DTI model using the ZIFAZAH language. The usage scenarios associated with the sample tasks are representative of some typical real-world visualization tasks of neuroscientists and neurological physicians with expertise in DTI in their clinical practices. The usages range from visualization customization and exploration to DTI data analysis, covering the main language features and functionalities of our current ZIFAZAH implementation.

In the following scenarios, Josh, an end user of ZIFAZAH, has a geometrical model derived from a brain DT-MRI data set wants to compose and explore visualizations of the data for diagnosis purpose. For each of the scenarios, Josh fulfills his task by programming a ZIFAZAH script that describes his thinking process for that task and then clicks the “Run” button to execute the script. Josh programs with ZIFAZAH syntax references showing on a help window and corrects any term that is typed incorrectly with the assistance of error messages displayed in the output window. Once the script is interpreted correctly, either the visualization gets changed or numerical values coming out in the output window, as the results of script execution. Scripts and running results are presented at the end of the description of each usage scenario.

5.1 Scenario 1: composing visualizations

To start with, Josh specifies a data file that contains the geometries of the brain DTI model using the LOAD command. As used in examples throughout this paper, the model contains five major fiber bundles that have been marked in its storage structure in a text file: corpus callosum (CC), corticospinal tracts (CST), cingulum (CG), inferior longitudinal fasciculus (ILF) and inferior frontal occipital fasciculus (IFO). By default, running this single statement gives a streamtube visualization of the model with uniform visual encoding across all major bundles and without depth encoding.

Suspicious of the association of a known disease named Corpus-Callosum-Agenesis (CCA) with the distribution of neural pathways at the intersection of the CC and CST bundles, Josh continues to customize the streamtube representation by mapping fractional anisotropy (FA) to tube radius along each CST fiber since he is interested in the FA changes of CST at the intersection, and encoding depth values of CC fibers to colors so that he can easily discern the genu and splenium fibers in the CC bundle along the depth dimension in the coronal view. Finally, Josh also wants to highlight the IFO fibers preferably represented with ribbons. Since the IFO bundle is roughly perpendicular to the CST bundle, he likes to take it as a reference as well. To achieve this task, Josh wrote the final script after error corrections as follows and got the result in the visualization view as shown in Figure 7.

```plaintext
LOAD "/home/josh/braindti.data"
SELECT "CC,CST,IFO"
UPDATE size BY FA IN "CST"
UPDATE depth BY color IN "CC"
UPDATE shape BY ribbon IN "IFO"
```

Figure 7: Screenshot of the visualization resulted from running the ZIFAZAH program written in scenario 1.

5.2 Scenario 2: examining ROIs

It is quite common that neurologists tend to examine particular regions of interest (ROIs) rather than the whole brain when using DTI visualizations. In this task, Josh is only interested in all fibers within the temporal lobe area that belong to the CG bundle and CST fibers in the parietal lobe area that have average linear anisotropy (LA) value no larger than a threshold to be determined. The SELECT command with relative spatial operations using the anatomical planes enables Josh to precisely reach the ROIs he desires.

To start with, Josh firstly aims to filter fiber tracts outside the temporal and parietal area by adjusting the three cutting planes with relative movements and then starts trying to reach the exact target fiber tracts using both fiber bundle filters and conditional expression related to LA. With respect to the LA threshold undecided, Josh initially begins with an estimate and then keeps refining until he gets the accurate selection of target fibers. In the end, he has a workable script written in ZIFAZAH as follows. As a result, Figure 8 shows the ROIs that Josh programs for.

```plaintext
LOAD "/home/josh/braindti.data"
SELECT "axial +63.35"
SELECT "sagittal +71"
SELECT "coronal -48.5"
SELECT "axial -0.25"
SELECT "sagittal +7.2"
SELECT "CC"
SELECT "LA <= 0.275" IN "CST"
```

5.3 Scenario 3: calculating metrics

Beyond visual examinations, neurologists often request quantitative investigations of their DTI models as well. In this scenario, Josh attempts to check the white matter integrity in his brain model due to the limited reliability of DTI tractography.

For a rough estimation of the integrity, he uses the CALCULATE command to retrieve the size, in terms of the number of fibers, and average FA of both the whole brain and representative bundles. Further, with the average FA he has requested before, Josh goes further to make use of it to kick out CST fibers with average FA below the bundle-wise average. Josh writes the following script and obtains what he needs.
debugging the script since many low-level computations and control logics behind the high-level syntax are hidden for the users. In order to minimize such drawbacks of the current ZIFAZAH design, the script interpreter has been developed to strictly check each current statement and stop further executions of the script once current return signals abnormal behaviours such as importing invalid data input and referring to unknown variables.

In addition, regarding the execution mode, the current implementation of ZIFAZAH does not follow a real-time interactive running mode by which the visualization is updated once the script changes. Instead, the programming interface requires a separate user interaction, such as clicking a button or pressing a key, for running the present script. This design is for the interface simplicity and lower computational performance requirement, although a programming environment with otherwise real-time update is easy to implement.

While at the prototype stage, ZIFAZAH is still under active development with an intention to add more useful features to our visualization language for the purpose of better user experience and more powerful language expressiveness from end-user perspectives in scientific domains. Some of the promising features are outlined as follows, which are also in our future plan for ZIFAZAH design and development.

**Concurrent multiple-model exploration:** While exploring more than one DTI models in order, i.e. switching data input from one to another using the LOAD command, has been supported, concurrent exploration of multiple models has not yet. However, requirements for doing so do exist among our end users. As an example, one typical case is to examine two brain models in which one is known as normal and another suspicious of a brain disease. This is not rarely seen in clinical practice since the side-by-side comparison is helpful for efficient recognition of cerebral anomalies or simply finding structural differences. Corresponding ZIFAZAH commands and related other type of symbols can be extended for such concurrent explorations. Among other changes, the evaluation of LOAD statement result to an identifier (a handle for instance) can be utilized to identify a specific model out of multiple ones simultaneously explored.

**Visual-aids for programming:** Even though programming provides controls more precise than visual interaction in many cases, such as moving the axial plane by 22.5 cm, in a 3D visualization environment, under some occasions it is hard to describe exploratory steps in the visualization. For example, with only an unverified picture in mind about the outline of a fiber bundle that features human brain suffering a particular type of disease, a neurologist would like to check if a given brain is afflicted with such disease by looking for any fiber bundles characteristic of the outline. In this context, a visual aid that allows the user to sketch the outline for matching target fiber bundles can be fairly effective while describing such outline in script is pretty difficult or at least far from being intuitive. Such visual aids can be integrated into ZIFAZAH, with which users are enabled to designate a semantic term in the language through visual sketching or drawing.

**Improved usability:** Although ZIFAZAH has been designed to be fully declarative and many features have been developed expressly for maximal usability, such as flat control structure and consistent syntax pattern, the usability of the overall programming environment can be further improved from two aspects. First of all, apart from a help window showing all symbols and syntactical details which has already been implemented, context-aware automatic word completion can be built into the script editor so that users would not need remember language keywords. Also, statement templates can be provided in the interface so that users can program a statement simply by filling blanks followed by clicking a button to confirm (then the statement will be added into the editor). Secondly, instead of only displaying error message after execution, highlighting error-prone words when they are being typed...
We would also like to thank their valuable comments for further en-
principles of our visual programming language were abstracted.
The authors are grateful to medical experts in DTI for their partici-
tial to help narrow down the gap between visualization designers
more features are being extended on top of current design. Among
main prospective features to follow up. By ZIFAZAH we have pre-
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That particularly aim at our
design goals.
We have also described representative usage scenarios of ZIFAZAH apart from many example scripts written in the language before.
The language when using it as end users.
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cements of ZIFAZAH language when using it as end users.

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