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Generalized Temporal Focus+Context Framework for Improved Medical Data Exploration

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Abstract Physicians use slices and 3D volume visualizations to place a diagnosis, establish a treatment plan and as a guide during surgical procedures. There is an observed difference in 2D and 3D visualization objectives of the various groups of specialists. We describe a generalized temporal focus+context framework that unifies different widely used and novel visualization methods. The framework is used to classify already existing common techniques and to define new techniques that can be used in medical volume visualization. The new techniques explore the time-dependent position of the framework focus region to combine 2D and 3D rendering inside the focus and to provide a new focus-driven context region that gives explicit spatial perception cues between the current and past regions of interest. An arbitrary-shaped focus region and no context rendering are two novel framework-based techniques that support improved planning of procedures that involve drilling or endoscopic exploration. The new techniques are quantitatively compared to already existing techniques by means of a user study.

Keywords Volume visualization · Visual perception · Evaluation studies · Focus+context · Generalized framework

Introduction

In the everyday practice of medical diagnosis and surgical planning, physicians rely on exploring 2D slices of the patient's anatomy. Computed tomography (CT) and magnetic resonance imaging (MRI) datasets often contain multiple series of dozens of slices a physician has to scroll through and examine in detail. Such slices provide only a 2D image of the necessary anatomy. Physicians have to mentally reconstruct the volume by scrolling through the images while trying to locate any target structures. Medical training and experience are crucial in the correct implicit volume reconstruction while high concentration is necessary for processing the small details.

To help physicians with the cumbersome task of data exploration, various 2D and 3D visualization techniques have been developed. These techniques often include rendering of slices and extracted 3D anatomical objects separately or together. Different medical specialists have different visualization needs. For example, one technique can be used by surgeons when they have to plan a surgical procedure. Another technique can be used by radiologists who need to explore the dataset and find abnormalities. However, most physicians use 2D slice or 2D+3D visualizations. While radiologists explore orthogonal slices by scrolling through them and mentally reconstructing the volumes, surgeons may prefer to see slices that can provide an improved understanding of the areas that make up the taken exploratory path. Moreover, radiologists may use 3D volume rendering to explore the whole dataset or the target object. Surgeons may use 3D renderings to identify structures that lie along the resection path and have to be either avoided or removed so that the target object is reached.

As presented by Kainz et al. [1], there are also cases when 2D visualizations are preferred over 3D volume rendering, and vice versa. While specialists prefer to use 3D visualizations to get an overview of the dataset, to investigate multimodal datasets and to exchange information between groups of specialists, 2D slice visualizations remain the preferred method when accurate planning of interventions is to be performed since slices do not suffer from occlusion.

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While current visualization systems support generic 2D and 3D renderings and their combination, they fail to provide tools that can unify the different approaches how radiologists and surgeons utilize them. Thus, we propose to use the focus+context paradigm [2] in order to define a generalized temporal visualization framework that can be used to not only define and compare most of the already existing techniques, but to also implement new improved techniques that can be used by radiologists and surgeons simultaneously. In our work, we use the focus+context technique as a generalized framework, where the dimensions of the focus and the context volumes can be changed to provide any of the already existing visualizations. Furthermore, the framework provides a novel way of interactively combining visualization techniques that physicians use, but are usually implemented by different systems or would require multiple windows that do not support explicit spatial relationship. While applications like MeVisLab [3], Slicer3D [4], and others provide multiple ways of rendering multimodal datasets, they have limited capabilities of addressing the different visualization needs of medical specialists within the same environment and do not support collaborative meetings. Unlike our framework-based visualizations, the limited interactive focus+context techniques within these systems require significantly longer interaction times in order to accurately locate abnormalities and understand their spatial relation to other anatomical regions.

The proposed new visualizations for improved dataset exploration and for more accurate surgery planning rely on the temporal change of the focus region and provide options for 2D, 3D, and a novel combined 2D and 3D sub-volume rendering inside the focus that has not been explored before within the focus+context paradigm. Our new focus-driven context technique utilizes animation approaches to provide explicit spatial perception between regions that have been considered important in the past and the current focus region. This animated region can be used to combine dataset modalities and to provide additional data. The framework supports multiple focus regions each controlled by a unique user and the definition of a new arbitrary-shaped focus region modifiable at runtime. Having all these visualizations implemented using the proposed framework, we provide a novel single system that displays different interactive visualization modalities simultaneously and can be used by specialists discussing medical cases collaboratively without the need to switch between rendering systems. As part of this work, we executed a user study that compared the newly proposed techniques to existing similar techniques in order to identify areas of improvements.

Background

Significant research in the past decade has been devoted to visualizing important dataset structures in detail while maintaining context awareness. Physicians often view datasets by using software designed to display one slice at a time in the axial, sagittal, or coronal planes. Many commercial and research systems [4–6] display the three orthogonal views in their own windows and the user uses a scrollbar to go through the sequence of slices. A 3D visualization of anatomical structures is displayed in a separate window in order to provide context and can be augmented by displaying the three axis-aligned slices in the same window. Such a 2D+3D approach provides more spatial cues, but it creates additional requirements of adjusting threshold values in order to visualize specific 3D features. Combination of 2D and 3D data has also been achieved by superimposition of 2D data onto a 3D volumetric rendering [7]. However, 2D+3D approaches have to be able to overcome occlusion of the 3D volume from other anatomical structures or the displayed 2D slices, as well as to provide depth perception cues for correct depth understanding. Tietjen et al. [8] have developed a 2.5D visualization that addresses volume and slice occlusion. However, their method requires initial segmentation of the important structures.

The necessity to further improve techniques used to display a 3D volume and slices within the same view has been addressed in [9]. Their proposed technique ExoVis provides a volume rendering where arbitrarily positioned slice placeholders display the corresponding slice on a “wall”. The rendering of slices on “walls” surrounding the volume has also been explored by König et al. [10]. These two approaches however provide limited explicit spatial perception cues and can cause disorientation since the user has to look at multiple rendering areas.

Much work has been done in addressing limited spatial relationship between 3D anatomical structures. An approach where one or multiple cutting planes are used to create exploded views has been introduced in [11] in order to provide explicit relationship information. Clipping volumes based on voxelized objects are used to cut away regions as presented in [12]. Improved spatial relationship perception is achieved by volume peeling in [13].

Another technique used in scientific visualizations for improved spatial relationship understanding between different regions and datasets is focus+context. Focus+context visualizations provide a context area that gives general spatial perception cues. The focus region of such visualizations is often referred to as a magic lens. A 3D geometry called a lens is used to interactively define the region of interest where different filtering and rendering techniques are applied. Focus+context visualizations have been used in graph visualizations where clutter and occlusion can severely decrease the understanding of data, and have been extended to 2D, 2.5D, and 3D visualizations. It has also been used as a distortion tool for better exploration—the focus area is magnified or applied to other deformations

[14, 15]. The first application of a magic lens in the medical domain for an improved dataset exploration was proposed by Viega et al. [2]. Other researchers have further extended the focus+context paradigm to multiple volumetric lenses [16], various volume distortions—e.g., zooming [17–19], and different techniques for volume rendering [20–22].

Focus+context visualizations are commonly used in dataset exploration or surgical planning systems. For example, [23] provides an illustrative focus+context visualization to explore regions of interest. Diepenbrock et al. [24] presented a resection tool in the shape of a magic lens. The main disadvantage of their approach is that it does not provide explicit spatial perception understanding between the provided detailed probe view and the other views. Rieder et al. [25] have also introduced a focus+context surgical tool. All computations and interactions are dependent on an initial region of interest selection. Burns et al. [26] have created a surgical visualization that assumes the focus region to be a 2D slice from a dataset or an ultrasound plane. 4D data has been rendered in the focus region in [27]; however, this type of visualization is used mostly for dataset exploration.

Novel rendering techniques within the focus region and how to define focus have also been explored. The focus region can be in the shape of an anatomical region of interest, thus only the important structure is visible [28]. A specific anatomy, for example blood vessels from the whole dataset as in [29], can also be used to define focus. The main disadvantages of such approaches are the need for dataset segmentation and the lack of an interactive way of defining different regions of interest at run time respectively. Focus-dependent regions used for displaying data by means of rendering modalities that are different from the ones in the focus area have been previously explored [30]. This work is different from ours since the rendering region we introduce does not depend on the shape of the focus, provides visibility of past focus regions, and changes over time. The animation-like approach of our work is conceptually similar to the work in [31]. However, our work uses an animation to record past focus regions and to provide explicit cues about the spatial relationship between past and current focus.

Typically, the volume displayed inside the lens of a focus+context visualization is always the whole volume that falls within the boundaries of the lens. Furthermore, focus+context techniques are often developed to help either surgeons or radiologists. Therefore, most of the existing techniques do not provide the needed visualization tools for a wide range of medical specialists. Multiple systems might have to be used for the accomplishment of, for example, surgical procedure planning. To achieve a wide range of capabilities for a single system, a framework that unifies all used visualizations is needed.

Materials and Methods

Generalized Temporal Focus+Context Framework

We introduce the use of a generalized temporal focus+context framework which is based on the observation that any existing visualization can be represented as having two 3D geometric regions (focus and context) with adjustable dimensions as presented in Fig. 1a. By changing the size of the two 3D regions (the black cuboid is considered the context region, while the red cuboid is the focus region), we can achieve any of the existing and most widely used visualizations. Further exploration of the focus and context regions and the temporal changes of the focus region within the framework provide us with new visualizations.

Classification of Already Existing Techniques

By changing the *x*, *y*, and *z* dimensions of each of the two regions from the framework, we can create the most common 2D, 3D, and 4D visualizations as summarized in Table 1. For example, in order to create a 3D volume augmented with a 2D slice as described in the "Background" section, the context region will be assigned dimensions equal to the context dataset, while the focus region will have dimensions equal to a single slice from the focus dataset—Fig. 1b. 3D rendering of the whole focus dataset with no context information can be achieved by assigning the dimension of the focus region equal to the whole focus dataset as shown in Fig. 1c. 3D focus+context visualizations are achieved by having the context region equal to the context dataset as in Fig. 1e. The focus region has dimensions smaller than the focus dataset. If the focus region has reduced *x* and *y* dimensions, and a depth equal to a single slice—Fig. 1d, we can achieve the visualization presented in [26].

Classification of New Visualizations

We developed new visualizations by exploring the interaction of the focus and context regions from the introduced framework. In all but one of these visualizations (Table 2), the context region has dimensions equal to the whole context dataset and the focus region has reduced dimensionality. The technique of "Inner sub-volume exploration" assumes that the context region is defined but ray-traversing it does not accumulate any color, therefore skipping this region. The time-dependent interaction with the focus region provides us with five novel techniques. These techniques are explained using the framework definition and are presented in Table 2.

In the first visualization, we allow the user to explore the slices that make up the focus volume, thus incorporating 2D slices in the focus+context paradigm. By recording the slices that have been explored over a time range, we provide a new

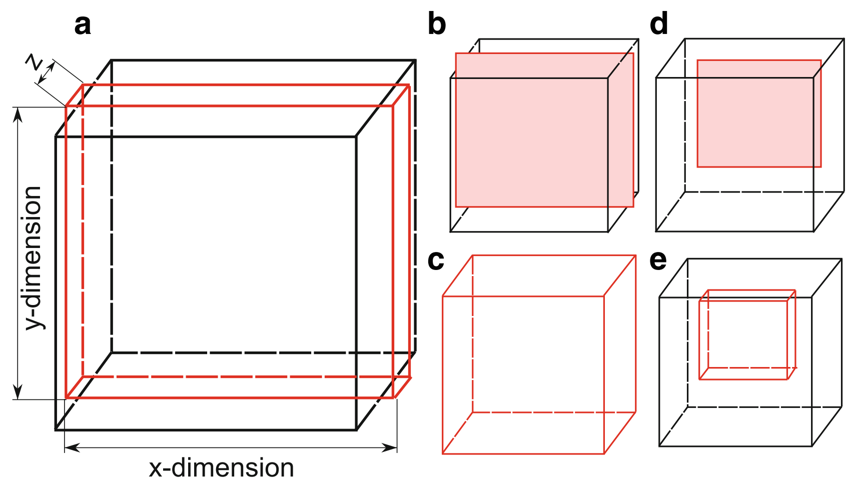

Fig. 1 Conceptual representation of the generalized focus+context framework. Any combination of 2D and 3D volumes can be viewed as having two 3D geometries of different size

way of studying the structure of objects inside the focus region by minimizing the amount of occluding objects.

Saving past focus region positions over a user-defined time span, we create a visualization that provides explicit spatial relationship perception. This time-dependent region called focus-driven context adds a third region where a combination of datasets and modalities can be displayed.

If past focus positions are saved and not replaced by newer positions after a time range, we can create any arbitrary-shaped 3D focus region. This region can be extremely complex depending on the user's interaction. Volume inside this arbitrary-shaped focus can be skipped to achieve an improved sculpting visualization, or rendered as a 3D volume to provide a visual evaluation of an executed drilling procedure.

Table 1 Existing visualization techniques described by the generalized temporal focus+context framework

Visualization	Representation using generalized temporal focus+context framework	
	Context	Focus
3D volume	Whole context dataset	*Z*-dimension equals 0
3D volume	*Z*-dimension equals 0	Whole focus dataset
Clipped 3D volume	3D geometry smaller than context dataset	*Z*-dimension equals 0
Clipped 3D volume	*Z*-dimension equals 0	3D geometry smaller than focus dataset
2D slice	Dimensions equal to single slice from dataset	*Z*-dimension equals 0
3D with 2D slice	3D geometry with dataset dimensions	Size equal to a single slice from dataset
Focus+context	3D geometry with dataset dimensions	3D geometry with reduced dataset dimensions
4D focus+context	3D geometry with dataset dimensions	3D geometry with reduced dataset. Dataset and position change over time

If no volume raycasting is done within the context region, we can create a visualization similar to virtual endoscopy procedures. The focus lens is moved in space as if it were an endoscope camera. It allows physicians to explore structures inside the datasets without being limited to hollow organs for the camera traversal.

The following sections describe each of the newly presented visualizations in detail.

Novel Visualizations for Dataset Exploration

Slice-Based Lens

Our first contribution is an extension of what visualization modality is visible inside the magic lens. Once the user has identified an anatomical structure of interest while using the 3D focus region (Fig. 2a), he can switch the visualization to a 2D slice rendering. The user can then explore the slices that make up the volume that was previously rendered in the 3D focus (Fig. 2b, c). Our approach is driven by the series of tasks that radiologists often perform—explore the whole volume and find the target area; then, concentrate on the selected region and explore it, paying attention to detail by looking at slices. With our approach, we allow the magic lens to visualize the important slice detail of the target volume found using the standard 3D rendering of the lens. At the same time, we also preserve the contextual information necessary for the spatial relationship understanding between different datasets.

Therefore, using the introduced method, one can switch from the volumetric rendering inside the focus volume to a slice rendering. The slice position varies between the back and front ends of the lens. Visualizing a slice deeper within the volume would require the lens to be moved further inside the volume. The user can scroll through the slices, and the lens position and orientation in 3D space is controlled using the mouse, an EM tracker, or Microsoft Kinect. This process is successfully executed using a standard focus+context

Table 2 Proposed new visualization techniques defined by the generalized temporal focus+context framework

Visualization	Generalized temporal focus+context framework	
	Context dimensions	Focus dimensions
2D inside 3D focus	Whole context dataset	One slice inside focus region. Focus region is smaller than dataset dimensions
2D+3D focus and 3D context	Whole context dataset	Focus region is smaller than focus dataset dimensions. Sub-regions of the focus volume are rendered in 3D
Focus-driven context	(1) Focus-driven context defined by past focus; (2) context with dimensions of whole context dataset	The focus region is smaller than the focus dataset dimensions. The rendering modality inside the focus area can be 3D, 2D or 2D+3D
Arbitrary focus region	Whole context dataset	Arbitrary shape defined by moving the lens in time
Inner sub-volume exploration	This region is skipped	Focus region is smaller than the focus dataset dimensions. The rendering modality inside it can be 2D or 3D

visualization as described in Kirmizibayrak et al. [32] and allows interactive movement of the focus region in 6 DOF.

Another advantage of this approach is that a necessity to explore a larger section of a 2D slice can be easily accommodated by extending the x and y dimensions of the focus region. Thus, we can display very small or very large sections of a slice, while still showing 3D context surrounding the focus. Having multiple 3D shapes for the focus region, we provide easy adjustments to the shape of the shown 2D slices—they can be in the shape of a square, circle, oval, or others.

The proposed extension of the focus+context visualization to show slices within the focus region aims at helping radiologists better understand the internal structure of the target volume by eliminating occlusion common for 3D visualizations. Surgeons can use the same visualization to explore structures along the planned resection path by seeing slices at arbitrary orientation. It also provides a slice visualization that physicians are comfortable with and often use when they have to see objects clearly.

2D+3D Focus and 3D Context

Many existing visualization techniques allow users to limit the visible volume using clipping planes. In Burns et al. [26], a front-clipping plane and the focus 2D slice define the rendered 3D region. In other focus+context visualizations a focal probe or a front-clipping plane is used to remove any volume in front of the probe position or the plane. However, no visualization explores the need for having a 3D focus region and rendering different sub-sections of it so that only certain areas are displayed. Using the generalized framework, we can redefine how sub-volumes inside the lens are rendered. We augment the sub-region with 2D slices to provide additional detail.

Driven by the commonly used visualization of combing 2D slices with 3D volumes as presented earlier, we aim to provide a new way of rendering sub-areas of the target region. To achieve this, we extend the 2D slice visualization inside the 3D focus region by recording the positions of the viewed slices over a period of time. The oldest and the most recently

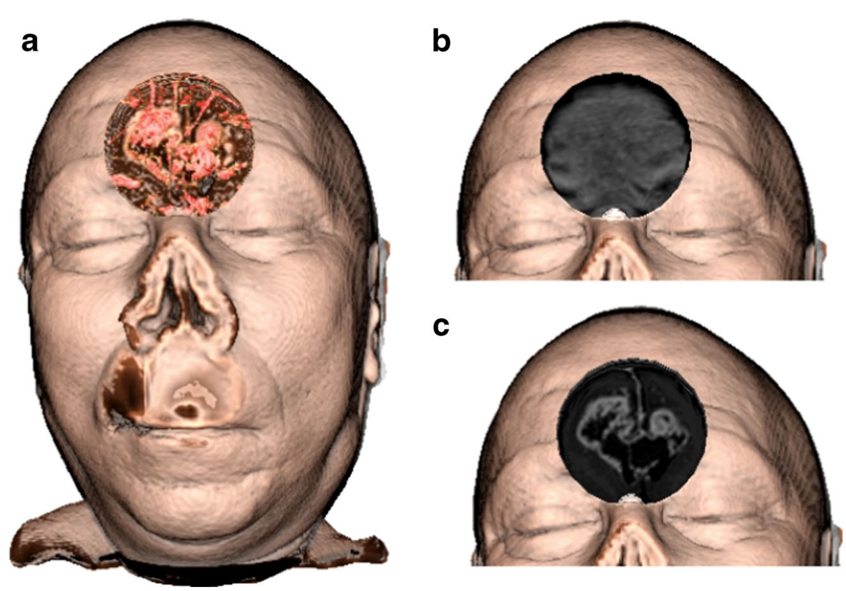

Fig. 2 Magic Lens visualization with 3D volume rendering inside the lens (**a**). Slice visualization inside the lens; slice corresponds to front end (**b**) and back end (**c**) of the lens

viewed and recorded slices are used for the definition of two time-dependent virtual cutting planes which define a 3D focus sub-region as shown in Fig. 3. The slice positions are saved in an array of size *N*, where *N* depends on the user-defined time span. If more than the time range has passed, newer slice positions are saved in a first-in first-out manner, causing the rendered sub-volume depth to change over time. When the user stops changing the slice position, the 3D volume visualization continues as an animation. The visible 3D volume will get smaller since the distance between the current and oldest slice positions over a constant time span decreases until the two slice positions are identical and only one single slice is visualized. Our raycasting algorithm uses the oldest and the newest slice positions at every frame (designated Slice 1 and Slice 2 in Fig. 3), therefore we can compute the positions where each ray passes through the two slices, thus speeding our rendering algorithm and maintaining real-time interaction.

The described interaction technique aims at combining both the volume visualization and the slice visualization within the lens in a manner that gives a better understanding of the internal structure of the volume in focus. This approach can achieve a rendering of the whole volume within the lens (Fig. 4a). It can also be successfully used to display the volume only between two consecutive slices (Fig. 4b), giving a more detailed understanding of the internal anatomical structures. Having two clipping planes defined by the explored slices, we can provide clear visibility of only the selected structures of interest. To prevent the loss of important details that might not be captured by the current transfer function, but could greatly contribute to the user's volume structural understanding, we made the back-most slice visible at every frame.

The described 3D sub-volume visualization can help both radiologists and surgeons achieve their exploratory goals. Radiologists can use this visualization to remove unnecessary objects inside the focus region and visualize only the target structure (for example a brain tumor). This way, they can clip away objects in front of and objects behind the tumor while still seeing slices that make up the brain tumor. In contrast, surgeons can use this visualization to first find the target structure using the 3D focus region, and then concentrate on smaller regions in front of the tumor. They can explore anatomical structures that lie along the resection path without the tumor obstructing their view. They can also see a detailed

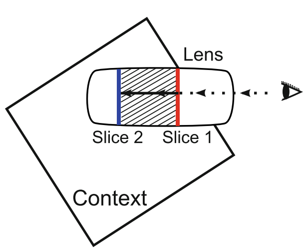

Fig. 3 Defining a sub-volume region by traversing rays only between the front-most (Slice 1) and back-most (Slice 2) recorded slices

view of the explored sub-volumes by concentrating on the 2D slices that are being scrolled through.

An interaction with the time-dependent slices and the rendered sub-volume can sometimes lead to limited understanding of the exact depth of the displayed volume. To provide a tool that displays information about the depth of the lens and what portion of the lens volume is visible at every time point of the interaction, we created a novel pie-like depth visualization tool (Fig. 5a) motivated by the distance ring tool introduced in [25]. Our depth tool can be used in any focus+context visualization. This tool's main purpose is to give approximate depth information about the lens and the rendered volume in order to help one understand where the rendered structure is with respect to the lens geometry and the context.

We assume that the circumference of the visualization tool corresponds to the full depth of the context dataset. Depending on the depth of the lens, the focus volume can be equal or less than the depth of the context volume. The lens depth is displayed in dark grey and shows the portion of the whole volume that falls within the lens geometry (in Fig. 5, the lens is 30 % of the whole volume depth). Within the lens, the two slices define the rendered sub-volume. Its depth is depicted in green and the position of the green section starts and ends at the corresponding slice locations within the lens. While the user changes the slice positions, the position and length of the green section keeps changing in order to provide real-time depth position information.

Focus-Driven Context

There is a lack of focus+context visualizations that explicitly show how past and current focus regions are related. We explored the temporal positions of the focus region within our generalized framework, and created a new region that alleviates the mental burden of implicitly inferring distance and shape relationship between multiple dataset landmarks. This new visualization named focus-driven context is defined by having a 3D focus geometry moved within the boundaries of the context region. The past focus positions over a user-defined time span are saved so that they define a complex shape directly dependent on the current focus position and that can be used to render various datasets and modalities.

Conceptually, we can think of this new rendering area as a sub-volume of the framework's context region, thus defining a hierarchy of multi-level context regions that can provide explicit relationship between structures from different regions. Unlike focus+context visualization where there is explicit relationship between focus and context only, the hierarchy of contexts provides two additional explicit spatial relationships—between focus and focus-driven context, and between focus-driven context and context.

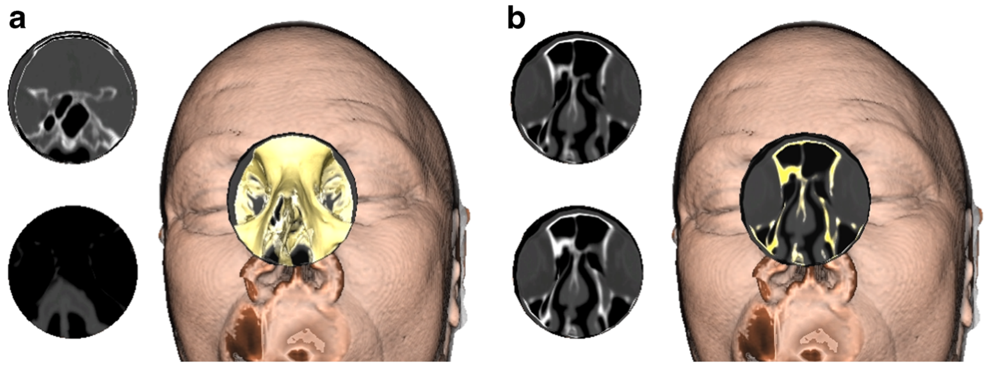

Fig. 4 **a** 3D rendering of the whole volume visible inside the lens with the corresponding front and back slices shown on the left. **b** 3D sub-volume rendering of a region between two consecutive slices

To achieve correct position rendering, the most recent N focus positions are saved in a first-in first-out principle. Therefore, regions that have been considered focus for more than a user-defined time span are replaced by more recent focus regions. This approach creates a geometry that changes its shape over time and follows the focus region as a trace in an animation-like manner. To provide additional detail from the context dataset inside the new region, a user-defined weight (w_{user}) and a trace distance weight (w_{distance}) are used to ensure that less context is visible in the most recently saved focus regions, while areas saved some time ago show more context features. The color and opacity at every pixel are computed using Eq.1. The values computed for the context and trace regions are merged using a weight w (defined in Eq. 2), where w_{distance} is the distance between the center of the focus region and the current focus-driven context pixel.

$$\mathrm{RGBA}_{\mathrm{final}} = (1-w)^{*}\mathrm{RGBA}_{\mathrm{context}} + w^{*}\mathrm{RGBA}_{\mathrm{trace}} \quad (1)$$

$$w = w_{user}{}^{*}(1.0 - w_{distance}) \quad (2)$$

Having three regions—focus, context, and focus-driven context, a user can assign different datasets and rendering modalities to each region. This allows optimal explicit spatial relationship inference between anatomical or functional structures. For example, physicians can use this technique to visualize a brain tumor inside the focus, while the context region shows the patient's skin. The focus-driven context can display the same dataset and modality rendering as the focus region (Fig. 6a), or display bone extracted from a co-registered CT scan (Fig. 6b) or brain activity from a co-registered PET scan (Fig. 6c). This visualization could provide an optimal understanding of how the tumor is related to various anatomical structures surrounding it. Focus-driven context also addresses the lack of explicit relationship between the 2D slice within the lens and the 3D rendering of the focus volume. The main focus area can be assigned to display the 2D slice visualization within the lens, while the 3D volume is rendered inside the focus-driven context region as in Fig. 6d.

This example shows how focus-driven context visualizations could be used by radiologists to explore the target object and relate it to areas far from the target but important for the placement of an accurate diagnosis. In contrast, surgeons can use this visualization to ensure clear visibility of the target region while displaying other regions along the incision path that can be from the same dataset as the focus or from another dataset.

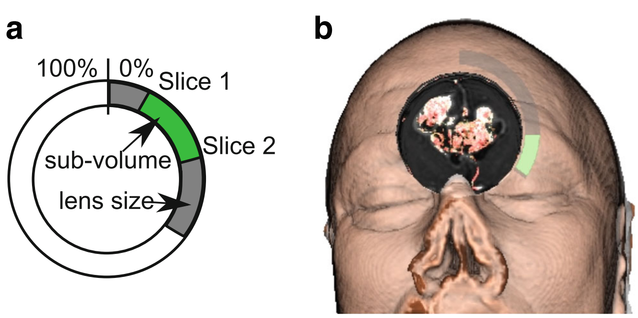

Fig. 5 **a** Depth visualization tool showing the length of the lens (in *grey*) with respect to the context volume and the volume spanned between slice 1 and slice 2 (*green*). **b** The tool applied in rendering the volume from Fig. 2a

Novel Visualizations Used in Surgical Planning

Arbitrary Focus Region Definition

All existing focus+context visualizations rely on a fixed-shape geometry used as a focus region. Focus lenses are usually of convex shape with adjustable size. Existing techniques support the simultaneous control of more than one focus regions. Such visualizations require the adjustment of the focus geometries separately, making them difficult to use. However, no visualization currently allows for the creation of complex modifiable concave lens shapes during runtime. Therefore, we explored time-dependent framework-based techniques that can allow us to sculpt the focus region.

In this visualization, we use a lens of a fixed convex geometry. While interacting with the visualization, the user can save positions of the lens at various time steps. The saved focus regions are rendered together, so that a focus region of

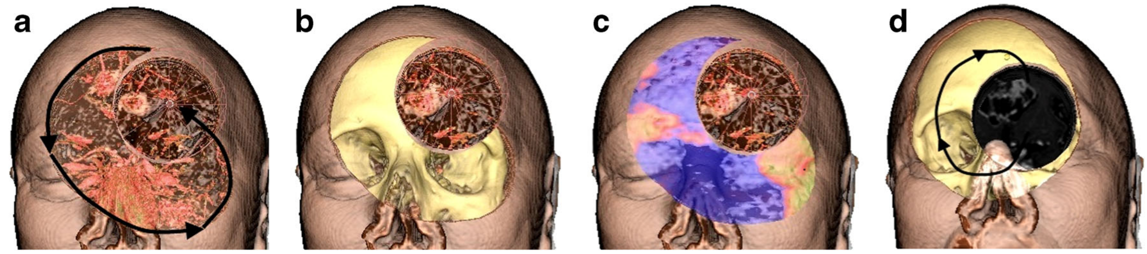

Fig. 6 Focus-driven context in different exploratory scenarios. The focus area can display the same dataset as focus-driven context (**a**), the focus-driven context can display different datasets – for example a CT scan (**b**) or a PET scan (**c**). **d** An MRI slice is visible in the lens, while focus-driven context displays 3D rendering of a CT scan. The *arrows* show the path of the lens

an arbitrary shape can be achieved. For example, we can use a lens of a cubic shape, and save four lens positions as shown in Fig. 7a. We can render the volume that falls within this new region in a preferred way—e.g., as a 3D volume or a 2D slice, or we can skip the traversal of any rays that fall within this arbitrary focus region as in Fig. 7b in order to visualize context dataset sculpting such as during surgical tissue removal procedures.

Some surgical interventions require removal of material that lie along the path to a target anatomical structure. Surgeons often have to practice such a tissue removal procedure using simulations so that they can explore the most suitable drill positions until the target is reached. However, the used drilling tools are filled-in 3D geometries and thus they do not give any information about what structures lie ahead of the drill, and whether vital anatomical structures will be removed if the drill is positioned in a certain place.

Our focus+context framework's tissue removal visualization can provide explicit visibility of structures to be removed or avoided. The chosen focus region geometry is used as the sculpting tool, referred here as a drill. While the lens can be rendered as a filled-in tool (Fig. 8a), it can show a 3D rendering of the volume that will be removed if the tool is placed at the current lens position (Fig. 8b). We can also display 2D slices inside the drill (Fig. 8c) so that the surgeon can explore the slices that make up the volume to be removed. Thus, one can precisely plan the next drill position so that important structures are avoided or removed. While moving the lens in space and designating structures as part of the focus, the system records the drill positions and creates an arbitrary-shaped region which is used to show the result of the executed drilling (Fig. 8d, e).

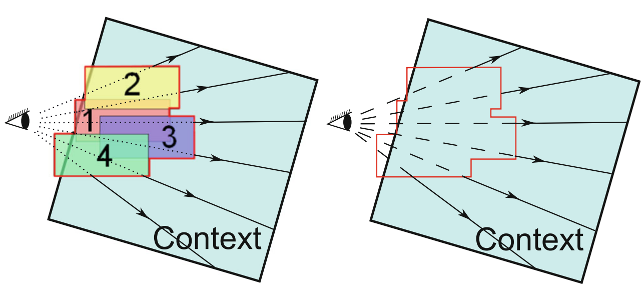

Fig. 7 Defining an arbitrary-shaped focus region. **a** Multiple lens positions can be saved and used as 3D focus. **b** Rays inside the lens are skipped while they are traversed when passing through context

After the tissue removal procedure is completed, current visualizations show what the final results are. However, the user cannot visually evaluate what structures have been removed since this information is lost. Having the introduced arbitrary-shaped focus region, we can visualize sculpting of the context and also show what has been removed. Since using our method, we have not done any modifications to the underlying volume or mesh, we can enable raycasting inside the new region and show the cut out structures—Fig. 8f.

Inner Volume Exploration

None of the current visualization techniques has explored the option of a focus region rendering while not displaying anything that lies within the context boundaries. Using the generalized framework, we introduce a visualization with no context displayed, while the focus region is volume-rendered (as seen in Fig. 9) and moved in 6DOF.

Such a visualization can be viewed as a modified virtual endoscopy visualization where the focus region is moved along the path of a virtual endoscope but provides additional volumetric information. Current virtual endoscopes use direct volume rendering or iso-surface extraction techniques in order to identify the boundaries of the traversed hollow object [33]. Virtual endoscopy provides an intuitive system that eliminates the necessity of performing an endoscopic procedure which often causes discomfort to the patient. However, virtual endoscopy supports the rendering of only those structures that lie inside the traversed hollow anatomy since its goal is to resemble the real procedure. Such a visualization technique would not be sufficient if a physician is looking for abnormal structures along either side of the hollow structure's walls.

In contrast, an inner volume visualization achieved by skipping the rendering of context and presented in Fig. 9 would show objects near the camera that are outside the traversed object's boundaries. For example, traversing the focus region along the nasal cavity (Fig. 10a) would display structures visible to a virtual endoscope, while also showing objects lying beyond the nasal walls (Fig. 10b). Furthermore,

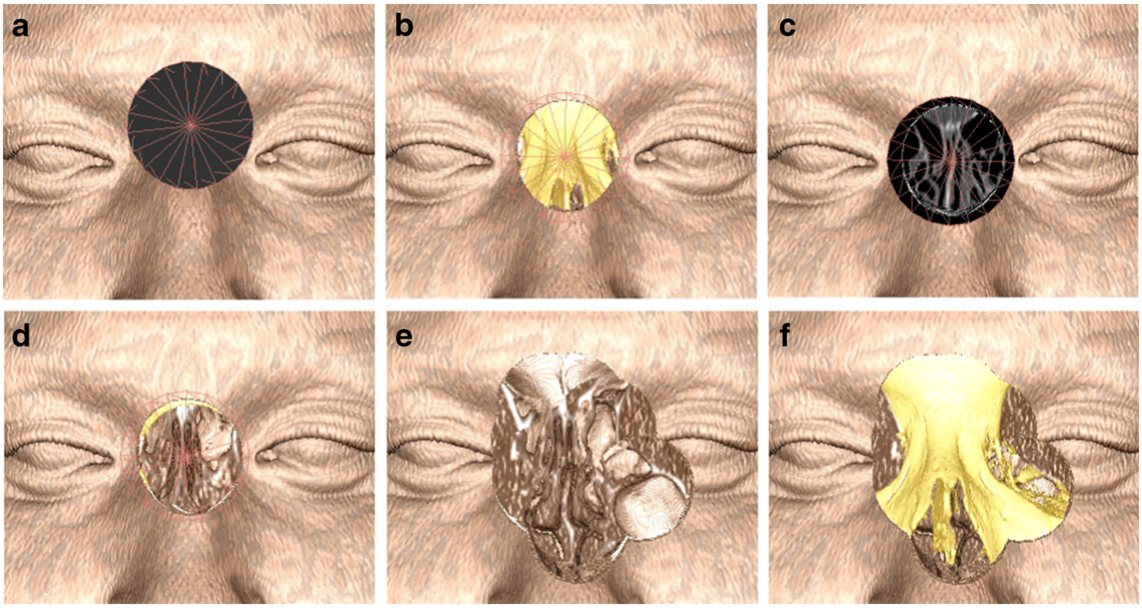

Fig. 8 Different modalities for tissue removal. **a** The drill is rendered opaque. **b** 3D volume inside the drill tool. **c** The back-most slice at the current drill position is shown. **d** The result from removing the section selected in image (**b**). **e** A large portion of the sinuses have been drilled out. **f** 3D rendering of the removed areas

the focus region can be moved in 6DOF and advanced further in to display the structures within the patient's sinuses as well as structures that lie beyond the hollow path of exploration as in Fig. 10c, d. This technique would not provide images identical to what is seen during endoscopy procedures. However, it can advance the physician's understanding of the patient anatomy and allow further exploration of regions not accessible during virtual endoscopy.

Another advantage of such a focus+context visualization is that only objects that lie within the boundary of the focus region are displayed. Thus, a surgeon can concentrate on the regions close to the camera and explore them in detail, before advancing the camera further in. This exploration can also be achieved in 2D by switching the rendering mode inside the focus region to 2D slices, providing a detailed structural view of the area of interest.

Group Meeting Application of the Framework

A typical hospital medical team meeting environment, as described in Olwal et al. [34], consists of various specialists who meet in a conference room setting to discuss a case. Remote users can participate in the meeting, which often requires them to have a PACS system installed on their machine. A radiologist sits at a workstation and selects slices of interest that are shown on a large screen with multiple views. Surgeons and other specialists would look at the projected slices and would have limited interaction with them, most often utilizing a laser pointer [35]. A novel interaction for users within the same room discussing a case has been presented in [34]. It can however cause distraction and physicians might not pay attention to what other specialists explore or annotate as important. Furthermore, current medical meeting environments with multiple users meeting in the same room can significantly benefit from 3D volume rendering of the datasets during the case discussion [36].

The introduced generalized focus+context framework can be applied to such conference room discussions. It can address the issue of different visualizations needed by each group of specialists, while maintaining independent interactions with the visualization so that everybody has control over what is being explored and discussed. We introduce a second focus region that has its unique lens assigned to it. Having two lenses, we can provide interactive focus regions for a surgeon and for a radiologist that are interacted with in the same environment. While a radiologist interacts with his focus region and explores the data using a technique and modality of his choice, the surgeon can interact with his focus region and display a visualization that provides information relevant to his planned task. We can generalize this visualization as assigning a visualization paradigm to each of the focus regions from a generalized focus+context framework with multiple focus regions.

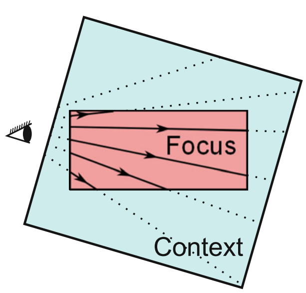

Fig. 9 Graphical representation of the inner volume exploration visualization

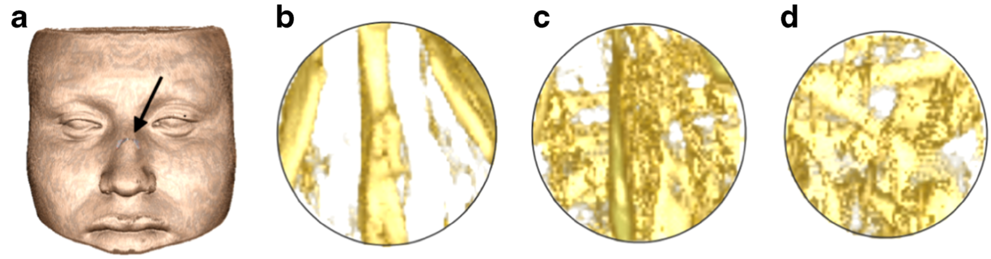

Fig. 10 Visualizing areas inside the volume. The lens is inside the sinuses (shown by an *arrow* in **a**). Moving the lens along the nasal cavity path reveals different volumetric structures (**b**, **c**, **d**)

Radiologists are often those that present a case and provide detailed information about target and surrounding structures. The introduced framework can display a bird's-eye view of the datasets in the radiologist view (Fig. 11). Surgeons have a separate window that displays a rendering of their focus region as if the virtual camera is placed at the back of the focus bounding box.

Currently our system supports two views—a radiologist view and a surgeon view. However, more than two views can be supported by the framework. Thus, the framework can be implemented as a collaborative interdisciplinary visualization system for a large number of users who interact with it by means of gestures utilizing Microsoft Kinect. Each view can be assigned its unique focus region, while all focus regions are displayed in the radiologist view so that there is a unifying control over what the multiple specialists explore.

Results

To evaluate the proposed new visualization techniques for dataset exploration and surgical planning, we executed a user study. The study was approved by the GWU IRB and all users gave their informed consent for participation. The study was performed by 18 users with median age of 28 years. In order to decouple domain knowledge, we recruited college-educated individuals. The study included three tasks, each of them comparing an existing technique to one of the newly introduced visualization techniques. The context dataset was the piggy bank dataset from the Volume Library, while the focus dataset contained cubes and spheres of different size and color adjusted according to the specific task. We used a non-medical dataset to remove the factor of anatomical knowledge from the study. The study was repeated twice in order to see if improvements of response time and accuracy will be observed between tries. Outliers were removed and average values per user were used. The normal distribution of the data was verified by the Shapiro-Wilk test ($p>0.07$).

The first task compared existing front-clipping plane techniques (FCP) for sub-volume exploration with the proposed approach of sub-volume exploration defined by the oldest and the most recently viewed slices considered to be the front and back clipping planes (FBCP) that define the rendering region. Users had to identify which of the two pairs of cubes from the focus dataset contains a gap. The second task compared the focus-driven context visualization to a standard focus+context visualization. Users were asked to find the largest cube closest to a feature from the context dataset and closest to the largest sphere from the focus dataset. In this task, we compared four visualizations—a small lens (SL), a large lens (LL), focus-driven context with weight for alpha blending of 0.25 (Tr1), and focus-driven context with weight for alpha blending of 0.05 (Tr2). In the third task, users were asked to drill starting from a small white cube positioned on the dataset surface until they clearly see a larger white cube at random depth from the surface. An opaque drill (OD) was compared to a transparent drill (TD) implemented using the magic lens visualization.

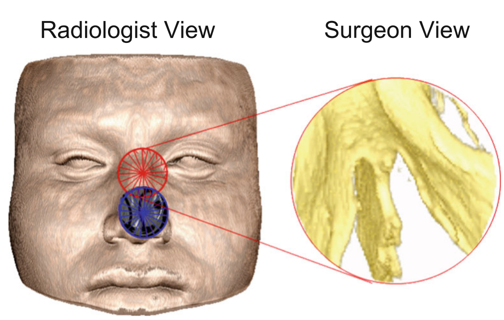

Fig. 11 Radiologist vs. surgeon view. Each view can be assigned different rendering parameters: e.g. CT slice inside the radiologist' lens (*blue*), 3D volume rendering inside the surgeon's lens (*red*)

Analysis of the Executed Study

As shown in Fig. 12, during the first repetition of task 1, FCP resulted in faster response times than FBCP (35.6 s vs. 37.0 s) but was less accurate than FBCP (86 vs. 90 %). During the second repetition, the average time of FCP reduced to $t=26.5$ s with accuracy of 86 %. FBCP resulted in an average response time $t=28.7$ s with increased accuracy of 95.8%. Compared to the first repetition, the second repetition was trending towards significant difference in accuracy. A performed paired-sample t test resulted in p value of 0.069. This hints at an accuracy improvement of FBCP the longer a user interacts with the technique.

The second task compared the four methods within each repetition separately as shown in Fig. 13. During the first try,

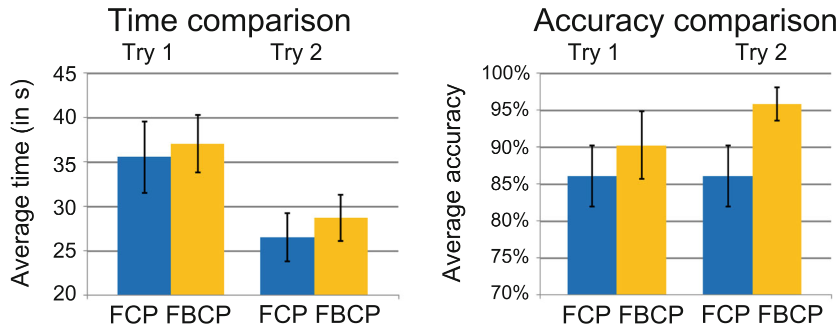

Fig. 12 Time and accuracy comparison with standard error between FCP and FBCP for each repetition of task 1

the fastest method was LL (t=19.6s), followed by Tr1 (t=20.1s), Tr2 (t=22.3s) and SL (t=22.7s). The most accurate method was LL (92 %), followed by Tr1 (88 %), SL (86 %), and Tr2 (83 %). During the second try, improvements of time and accuracy were observed. LL remained the fastest method (t=12.9s), followed by Tr1 (t=14.5s), Tr2 (t=16.5s), and SL (t=17.3s). The accuracy improved with LL and Tr1 having an accuracy of 93.6 %, while Tr2 and SL resulted in an accuracy of 91 %. In the first repetition, significant differences in response time were observed between SL and LL, where a paired-sample t test resulted in $t(17)=2.162$, $p=0.045$. One-way repeated measures analysis of variance (ANOVA) was applied to the data from the second try. Mauchly's test resulted in a violation in the assumption of sphericity ($\chi^2(5)=13.9$, $p=0.016$). The degrees of freedom were corrected using Greenhouse-Geisser estimates of sphericity ($\varepsilon=0.68$). One-way ANOVA resulted in significant time difference between the four techniques ($F(2.03,34.4)=6.18$, $p=0.005$). Pairwise post-hoc comparisons (two-tailed t tests) showed that this result was due to significant differences in response time between SL and LL ($t(17)=3.6$, $p=0.003$), between SL and Tr1($t(17)=2.51$, $p=0.023$), and between LL and Tr2 ($t(17)=-2.88$, $p=0.010$).

For the drilling task, both repetitions were analyzed simultaneously since the average time was dependent on the depth position of the target object. On average, OD was slower (t_{avg}=24.0 s) than TD (t_{avg}=19.3s). To compute accuracy, we calculated the distance between the target position and the end position of the drill. The target cube was 20 voxels deep. The results are shown graphically on Fig. 14. On average, TD gave an error of 1.4 voxels, while OD gave an error of 6.21 voxels. Paired-sample t test analysis resulted in identifying TD to be significantly faster ($t(17)=3.352$, $p=0.004$) and more accurate ($t(17)=2.576$, $p=0.02$) than OD.

Discussion

The analysis of the user study showed that in general, the new visualization techniques demonstrate time and accuracy improvements over other already existing techniques for dataset exploration and surgical planning. Furthermore, using the generalized framework to implement all compared visualization, we were able to create a system that can support and easily compare any combination of visualizations.

More specifically, having the flexibility to control two clipping planes (a front and a back one), users obtained a better understanding of the structure of volumetric objects. Even though the adjustment of two planes resulted in slightly longer interaction times, the higher observed accuracy shows that users should be given the possibility to explore arbitrarily positioned sub-volumes within a focus region. We believe that there will also be a significant accuracy improvement if this technique is applied to medical datasets, where displaying the back-most slice will add additional information regarding the anatomical structures. Therefore, it is important to note that some medical dataset exploration tasks would further benefit from a sub-volume visualization—for example, studying the inner structure of small anatomical objects or understanding depth relationship between structures.

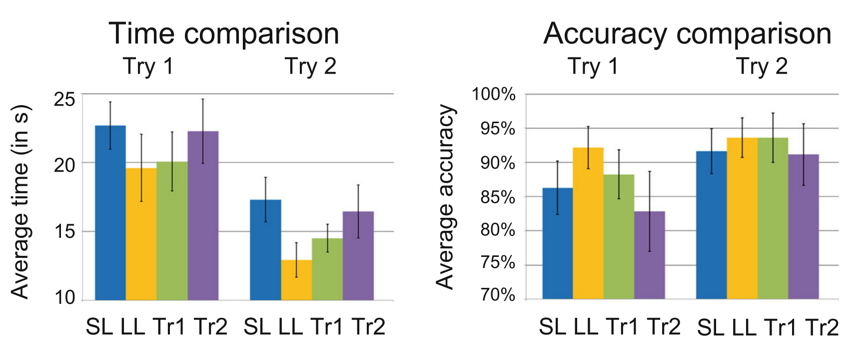

Fig. 13 Time and accuracy comparison with standard error between SL, LL, Tr1, and Tr2 for each repetition of task 2

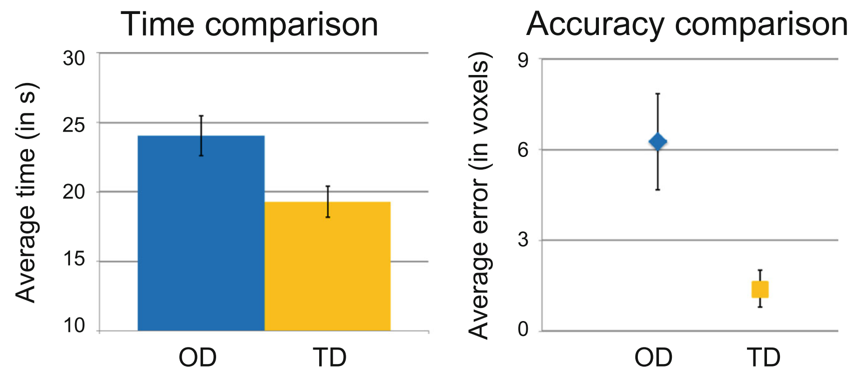

Fig. 14 Time and accuracy comparison with standard error between OD and TD

Another important new observation is that having a focus-driven context visualization gives a faster and more accurate spatial relationship perception when compared to a small focus region. In medical exploratory tasks where the focus region is expected to be small so that enough context is visible, having a focus-driven context can augment the spatial cognition of target regions. Furthermore, response time and accuracy of focus-driven context improves with time, so that users accustomed to this visualization will perform more accurately and faster compared to other techniques when performing complex tasks. Another conclusion is that focus+context visualizations should provide adjustable size lenses since every exploratory task might require a different focus size in order to achieve an optimal spatial relationship understanding.

Surgical planning often involves multiple planning sessions until the most accurate resection path is identified. By using a focus+context visualization and having the focus region selected as the drill, users can see different modality renderings of the region to be removed. This will ensure faster and more accurate path planning, which is important for many surgeons who need to plan multiple surgeries every day.

Conclusions

The familiarization and extensive practice of radiologists and surgeons to read 2D slices and implicitly infer the volume surrounding the target object has been the driving concept in the introduced visualization techniques. This paper describes a new approach that extends the focus+context paradigm to a generalized temporal visualization framework that supports the comparison of existing techniques and the identification of new techniques that can be used for improved medical dataset exploration and for surgical planning. The two main goals of the new visualizations are to combine the different visualization needs of medical specialists, and to improve the spatial perception, accuracy, and time performance of different groups of users by extending existing techniques. Using the proposed framework, we can address the differentiation of preferred visualization techniques that radiologists and surgeons use, so that we can unify these requirements within a novel single system that supports their simultaneous usage.

The five newly described visualization techniques rely on the time-dependent user interaction with the focus region. 2D slice, 3D sub-volume, or focus-driven context techniques can provide additional cognitive information in dataset exploration tasks. Users can interact with the volume by scrolling through the slices within the focus region, which are also augmented with a sub-volume rendering. The most recent and the oldest saved slice positions are used to define a sub-volume that reveals additional details of the internal structure of the target objects. Therefore, visual obstruction of the inner structures by the surface of the target volume can be avoided by allowing smaller sections of the volume to be displayed. The time-driven approach of this work helps users not only to interact with the volume in real-time, but also to explore the anatomical structures in an animation-like way. Less cognitive effort is required at intermediate steps, and more attention can be directed towards a better spatial and shape understanding of internal structures and multiple focus areas. Furthermore, these interactive visualizations can be enabled at the same time, providing explicit information and reducing the need for switching between techniques.

Visualizations defined by the framework can also address surgical planning simulations that can benefit from accuracy and time improvements. Using the focus region as a drill or a modified virtual endoscope, we can visualize more structures of interest while reducing the time needed to plan a procedure. As shown by the conducted user study, drilling simulators can significantly benefit by using focus+context approaches so that surgeons can plan the incision path with more accuracy, thus improving the success rate of the performed procedure.

This framework can thus lead to a more precise view of the abnormalities involved, augment multidisciplinary communication, and help to further define the nature and extent of pathology or the results of therapy. This may also be useful for the surgical planning and postoperative localization of medical implants and devices. In addition, this approach may have valuable applications beyond the clinical realm, including improved visualizations for scientists in more distant fields, medico-legal illustration modes, and teaching anatomy and pathology.

The next step of this work involves the design and execution of a second user study aimed at clinicians. Tasks involving dataset exploration and surgical planning using medical datasets (MRI and CT) will be provided in order to evaluate the execution time and accuracy when using the described framework techniques.

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References

1. Kainz B, Portugaller RH, Seider D, Moche M, Stiegler P, Schmalstieg D: Volume visualization in the clinical practice. In: Proceedings of the 6th international conference on Augmented Environments for Computer-Assisted Interventions. Berlin, Springer-Verlag, 2011, 74-84
2. Viega J, Conway MJ, Williams G, Pausch R: 3D magic lenses. In: Proceedings of the 9th annual ACM symposium on User interface software and technology. 1996, 51-58
3. MeVisLab. Medical Image Processing and Visualization. Available at: www.mevislab.de/. Accessed on Oct 09, 2013
4. Slicer3D. Multiplatform, free and open source software package for visualization and medical image computing. Available at: www.slicer.org/. Accessed on Oct 09, 2013
5. Caban JJ, Joshi A, Nagy P: Rapid development of medical imaging tools with open-source libraries. J Digit Imaging 20(supplement 1): 83–93, 2007
6. GEHC MicroView, Parallax Innovations. Available at http://microview.sourceforge.net/. Accessed 5 November 2012
7. Hachaj T, Ogiela MR: Framework for cognitive analysis of dynamic perfusion computed tomography with visualization of large volumetric data. J Electron Imaging, 21(4), Article Number: 043017, 2012
8. Tietjen C, Meyer B, Schlechtweg S, Preim B, Hertel I, Strauß G: Enhancing slice-based visualizations of medical volume data. In: Proceedings of EuroVis'06, 2006, 123-130
9. Tory M, Swindells C: Exovis: An overview and detail technique for volumes. Technical Report SFU-CMPTTR2002-05, Computing Science Dept., Simon Fraser University, 2002
10. König A, Doleisch H, Gröller ME: Multiple views and magic mirrors—fMRI visualization of the human brain. TR-186-2-99-08, 1999
11. Bruckner S, Gröller ME: Exploded views for volume data. IEEE Trans Vis Comput Graphics 12(5):1077–1084, 2006
12. Weiskopf D, Engel K, Ertl T: Interactive clipping techniques for texture-based volume visualization and volume shading. IEEE Trans Vis Comput Graphics 9(3):298–312, 2003
13. Correa C, Silver D, Chen M: Feature aligned volume manipulation for illustration and visualization. IEEE Trans Vis Comput Graphics 12(5):1069–1076, 2006
14. Sarkar M, Brown MH: Graphical fisheye views of graphs. In: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, ACM, New York, NY, USA, 1992, 83-91
15. Pindat C, Pietriga E, Chapuis O, Puech C: JellyLens: content-aware adaptive lenses. In: Proceedings of the 25th annual ACM symposium on User interface software and technology, 2012, 261-270
16. Borst CW, Tiesel JP, Best CM: Real-time rendering method and performance evaluation of composable 3D lenses for interactive VR. IEEE Trans Vis Comput Graphics 16(3):394–410, 2010
17. LaMar E, Hamann B, Joy KI: A magnification lens for interactive volume visualization. In: Proc. 9th Pacific Conf. Computer Graphics and Applications, IEEE Press, 2001, 223-233
18. Yang Y, Chen JX, Beheshti M: Nonlinear perspective projections and magic lenses: 3D view deformation. IEEE Comput Graph Appl 25(1):76–84, 2005
19. Wang L, Zhao Y, Mueller K, Kaufman A: The magic volume lens: an interactive focus + context technique for volume rendering. IEEE Visualization, 2005, 367-374
20. Rossler F, Botchen R. P., Ertl T: Dynamic shader generation for GPU-based multi-volume ray casting. IEEE Comput. Graph. Appl., 28(5): 66-77, 2008
21. Plate J, Holtkaemper T, Froehlich B: A flexible multi-volume shader framework for arbitrarily intersecting multi-resolution datasets. IEEE Trans Vis Comput Graphics 13(6):1584–1591, 2007
22. Kirmizibayrak C, Yim Y, Wakid M, Hahn J: Interactive visualization and analysis of multimodal datasets for surgical applications. J Digit Imaging 25(6):792–801, 2012
23. Svakhine N, Ebert DS, Stredney D: Illustration motifs for effective medical volume illustration. IEEE Comput Graph Appl 25(3):31–39, 2005
24. Diepenbrock S, Praßni JS, Lindemann F, Bothe HW, Ropinski T: Interactive visualization techniques for neurosurgery planning. In: Proceedings of Eurographics, 2011, 13-16
25. Rieder C, Ritter F, Raspe M, Peitgen HO: Interactive visualization of multimodal volume data for neurosurgical tumor treatment. Computer Graphics Forum 27(3):1055–1062, 2008
26. Burns M, Haidacher M, Wein W, Viola I, Gröller ME: Feature emphasis and contextual cutaways for multimodal medical visualization. In: Proceedings of the 9th Joint Eurographics / IEEE VGTC conference on Visualization. Eurographics Association, 2007, 275-282
27. Gasteiger R, Neugebauer M, Beuing O, Preim B: The FLOWLENS: a focus-and-context visualization approach for exploration of blood flow in cerebral aneurysms. IEEE Trans Vis Comput Graphics 17(12):2183–2192, 2011
28. Viola I, Kanitsar A, Groller M. E.: Importance-driven volume rendering. In: Proceedings of the conference on Visualization '04 (VIS '04). IEEE Computer Society, Washington, DC, USA, 2004, 139-146
29. Hauser H, Mroz L, Italo Bischi G, Groller ME: Two-level volume rendering. IEEE Trans Vis Comput Graphics 7(3):242–252, 2001
30. Luo Y: Distance-based focus+context models for exploring large volumetric medical datasets. Comput Sci Eng 14(5):63–71, 2012
31. Sikachev P, Rautek P, Bruckner S, Gröller ME: Dynamic focus+context for volume rendering. In: Proceedings of Vision, Modeling and Visualization, 2010, 331-338
32. Kirmizibayrak C: "Interactive volume visualization and editing methods for surgical applications". Ph.D. Dissertation, Department of Computer Science, The George Washington University, Washington, DC, 2011
33. Rogalla P, Terwisscha Van Scheltinga J, Jamm B: Virtual endoscopy and related 3d techniques. Springer-Verlag New York, LLC, 2001
34. Olwal A, Frykholm O, Groth K, Moll J: Design and evaluation of interaction technology for medical team meetings. In: Proceedings of the 13th IFIP TC 13 international conference on Human-computer interaction—Volume Part I, Springer, Berlin, Heidelberg, 2011, 505–522
35. Li J, Robertson T, Hansen S, Mansfield T, Kjeldskov J: Multidisciplinary medical team meetings: a field study of collaboration in health care. In: Proceedings of the 20th Australasian Conference on Computer-Human Interaction: Designing for Habitus and Habitat, ACM, New York, NY, USA, 2008, 73-80
36. Groth K, Frykholm O, Segersvard R, Isaksson B, Permert J: Efficiency in treatment discussions: a field study of time related aspects in multidisciplinary team meetings. 22nd IEEE International Symposium on Computer-Based Medical Systems, 2009, 1–8