

Exploration of virtual and augmented reality for visual analytics and 3D volume rendering of functional magnetic resonance imaging (fMRI) data

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Abstract—Statistical analysis of functional magnetic resonance imaging (fMRI), such as independent components analysis, is providing new scientific and clinical insights into the data with capabilities such as characterising traits of schizophrenia. However with existing approaches to fMRI analysis, there are a number of challenges that prevent it from being fully utilised, including understanding exactly what a ‘significant activity’ pattern is, which structures are consistent and different between individuals, comparative analysis across the population, and how to deal with imaging artifacts such as noise. Interactive visual analytics has been presented as a step towards solving these challenges by presenting the data to users in a way that *illuminates* meaning. This includes using circular layouts that represent network connectivity and volume renderings with ‘in situ’ network diagrams. These visualisations currently rely on traditional 2D ‘flat’ displays with mouse-and-keyboard input. Due to the constrained screen space and an implied concept of depth, they are limited in presenting a meaningful, uncluttered abstraction of the data without compromising on preserving anatomic context. In this paper, we present our ongoing research on fMRI visualisation and discuss the potential for virtual reality (VR) and/or augmented reality (AR), coupled with gesture-based inputs to create an immersive environment for visualising fMRI data. We suggest that VR/AR can potentially overcome the identified challenges by allowing for a reduction in visual clutter and by allowing users to navigate the data abstractions in a ‘natural’ way that lets them keep their focus on the visualisations. We present exploratory research we have performed in creating immersive VR environments for fMRI data.

Keywords—*Virtual/Augmented Reality; 3D volume rendering; functional Magnetic Resonance Imaging; Visual analytics;*

I. INTRODUCTION

Deciphering the enigma of the brain is often considered to be the final frontier of modern medical research. Burgeoning initiatives such as the Human Connectome Project [1] and the Human Brain Project [2] highlight the emphasis placed on this task. One of the key pieces of the puzzle is thought to be an understanding of the functional

system of the brain at rest and when performing specific tasks, ranging from touching objects, to viewing images, listening to music, and talking or singing [3]. A common method of acquiring these brain data is through functional magnetic resonance imaging (fMRI), which depicts a time-series of blood oxygen level dependent contrast imaging. These images describe the areas of the brain that are active at a certain point in time, and are often distilled into functional connectivity networks, which exhibit specific characteristics for different population sub-groups [3]. Statistical analysis of functional connectivity networks allows experts to detect and understand alterations related to diseases and disorders, e.g. Alzheimer’s disease [4] or schizophrenia [5].

In recent years, statistical network analysis of fMRI has become much more complex with the availability of powerful computational resources and development in sophisticated algorithms. These include, for example, the use of topological network approaches, modelling and inferential methods and machine learning [6, 7]. However, to date, it is unknown as to exactly which structures are consistent and which are different between the subjects, at different time points for one subject, and among population groups [8]. There are four primary requirements of fMRI data analysis that innovative visualisations can potentially address. These are: (i) to identify similarities and differences between individuals and across populations; (ii) to alleviate the problems of noise in the data, e.g. in time-series data; (iii) to assist in defining what significant activity patterns are and how to interpret them; and (iv) to investigate changes over time for one subject and/or population groups. Thus, the development of an intelligent, meaningful and effective interactive visualisation of fMRI connectivity networks is an important need for its ability to advance analysis. This can be achieved by exposing the complexities of the data, via supplementary visual aids, in a way that the human user can recognise patterns and insights that may be missed in statistical processing.

In response to the first requirement, visualisation approaches can be used to complement statistical analysis by presenting the results as well as raw data abstractions in a

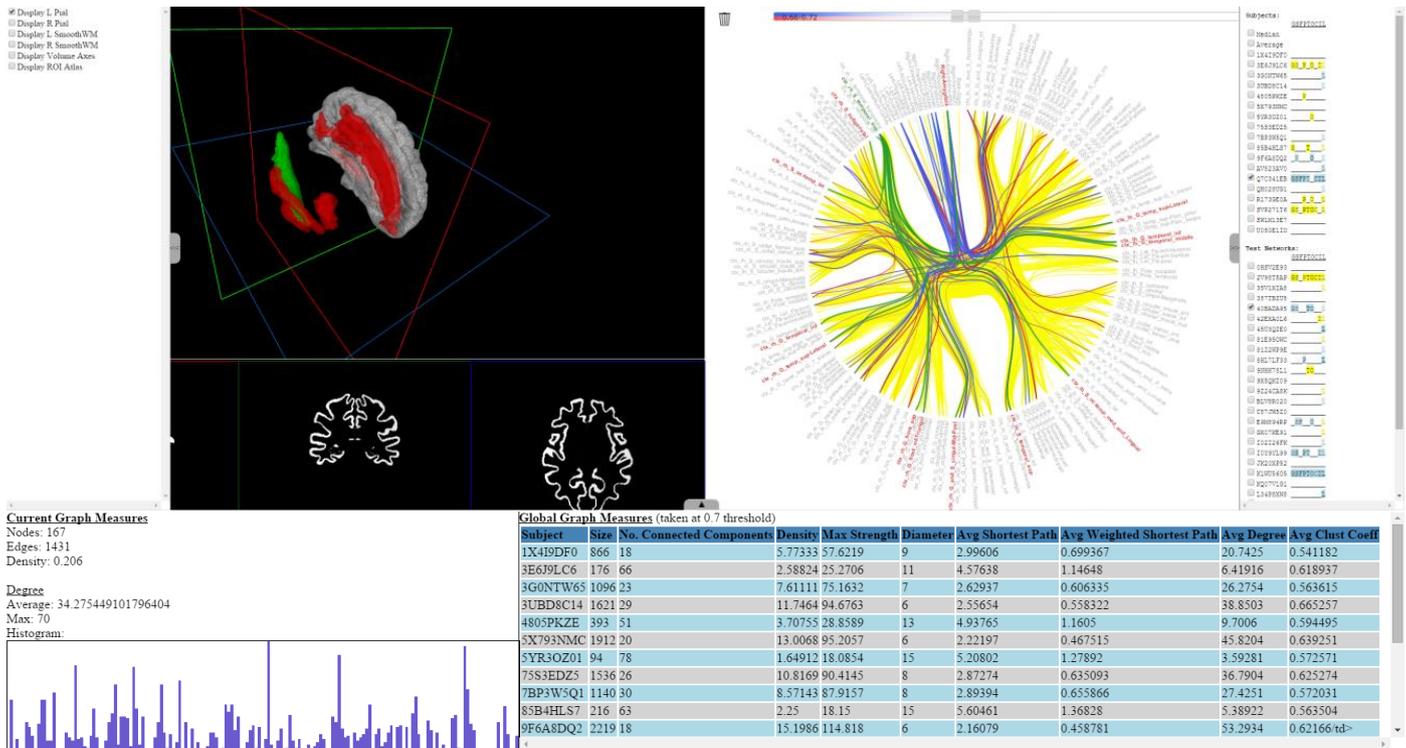


Fig. 1. Overview of the CereVA interface comparing two fMRI correlation networks: 3D rendering and volume display on the left; network abstraction on the right; statistical network analysis at the bottom. On the rendering, the green area is the selected node while the red ones are the correlated regions, within the current threshold. On the radial network abstraction, yellow background edges are highly similar, high correlation edges; blue and red edges are correlations within the specified threshold where blue edges have a higher correlation in the first subject's network and red in the second; green edges show the correlations for the selected node, which match nodes highlighted in the 3D rendering on the left. This image is from our previous study in [13].

way that elucidates similarities and differences. For example, displaying two heatmaps side-by-side can highlight differences more meaningfully than simply stating that a voxel group has an intensity difference. Regarding requirement two, as fMRI data is a time-series wherein activation patterns last for different durations than acquisition intervals, creating an average 'snapshot' of fMRI connectivity is a common practice. Moreover, as the time-series is noisy with unknown, individual baselines, spatial smoothing is commonly applied. This leads to imprecision and uncertainty in the data [9]. Meaningful, interactive visualisations that present this data have the potential to bare these imperfections to an expert in a manner that cannot be achieved through statistical analysis alone. Additionally, a lack of understanding about what constitutes 'significant activity' and how to measure it, requirement three, results in extreme variability of outcomes and findings between statistical techniques [10]. Thus, by combining visual analytics environments that are accompanied by pre- and post-statistical analysis, we can guide experts' understanding of the data and what is considered 'significant' or meaningful. Finally, considering the fourth requirement, visualisation techniques that assist understanding of the first three requirements can be combined to demonstrate changes over time. Similar to comparing differences, these can better highlight changes in brain activity, e.g. through animation. Despite these claims, however, current methods for visualising fMRI data struggle to cope with displaying an

uncluttered, meaningful abstraction that still contains innate anatomical ordering; one of the more important aspects of fMRI analysis [11]. This places extra strain on researchers as they are required to either mentally reconstruct the brain's anatomy, or mentally de-clutter the interface prior-to, and while, attempting to recognise patterns in the data.

There have been attempts to address these problems through visual analysis of functional data, as presented by Margulies et al. [11]. For these techniques to be meaningful, the fMRI visualisation requires a tight coupling of the correlation network and the anatomical structure [11]. Balancing the intricacies of this combination with the innate complexity of the data itself in a clear abstraction presents a difficult challenge for existing and emerging solutions. To facilitate this balance, current solutions generally take one of two approaches. The first is to display the connectivity network, e.g. as a ball-and-stick model, or as glyphs, within a 3D visualisation of the brain, e.g. BrainNet Viewer [12], connectivity glyphs [13]. While this method supplies strong anatomical reference, it implies direct pathways for edges that may not exist, especially considering that fMRI is the correlation of blood-oxygen activation in two, possibly unrelated, areas and not information that travels from one to the other. Moreover, the 'in situ' views result in a large amount of visual clutter that can make pattern recognition difficult. This sways the balance towards anatomical context, but it results in reduced readability and pattern recognition. The other common visualisation approach is to present the

correlation data on an anatomically ordered abstraction, such as a radial layout [14] or a heatmap. This style of visualisation solves the issue of implied pathways while still holding some anatomical information, however it does require mental reconstruction from the user to transpose the anatomical label(s) to 3D space. While these visualisations improve readability and pattern recognition, they reduce the anatomical context. A final, emerging visualisation solution, CereVA [15], which will be discussed in Section II, attempts to address both requirements by presenting a readable abstraction alongside the anatomical context. However, this approach is still limited by traditional mouse-and-keyboard interfaces as it presents almost double the information on a simple display that only allows point-and-click methods of interaction. This limits the interpretation of the complex data, e.g. as a user can only directly interact with one side of the visualisation at a time. Moreover, as the 3D is a representation on a 2D surface, the sense of anatomical location could be improved through immersive technology. Similarly, with current ‘flat’ displays, visualising a third dimension on the network abstraction, e.g. raising region of interest (ROI) nodes above the network, or displaying further contextual data around the network results in a prohibitive increase in visual clutter. This is further exacerbated when considering temporal fMRI data, as it requires a fourth dimension to be considered.

A potential method of solving this problem is to display the visualisations in virtual reality (VR) or augmented reality (AR). VR creates immersive computer-generated environments in which the users can feel more contextually present, minimising the effects of external factors on cognitive load. VR headsets contain a head-mounted display (HMD) that renders an immersive 3D environment with sensors tracking the wearer’s movements and location. Recent projects including Oculus Rift [16], Project Morpheus [17] and Open-Source Virtual Reality for Gaming (OSVR) [18] have resulted in affordable and accessible VR headsets that can be applied to research at a consumer level. Meanwhile, AR is a related concept in which devices render objects in a user’s physical environment. AR has traditionally been performed on screens as they project a camera feed, such as on smartphone devices. More recently HMDs have been introduced where renderings are displayed on a transparent screen before the user’s eyes. The most notable of these devices is Microsoft’s HoloLens (CITE). Using additional navigating devices, e.g. Leap Motion controller (CITE), Microsoft Kinect (CITE), the users can control their environment in a natural way that engrosses them in their data and designs. This is in response to a concept that has been around since the 1990’s of making interfaces as ‘invisible as possible’, minimising the gap between a user’s intent and the system’s execution (CITE: Lee). ‘Natural’ navigation techniques, which tie in tightly with VR and AR, have been presented as a solution for problems such as (i) ‘drowning in functionality’ of hierarchical menus and multitudinous buttons of traditional interfaces; (ii) constraints of mapping 3D data on 2D screens; and (iii) inherent visual complexity when presenting data in a constrained screen-based environment (CITE: Lee). Coupling the immersive benefits of VR/AR with intelligent,

interactive visual analytics and medical imaging data hence has the potential to revolutionise fMRI innovation and analysis by mitigating the inherent limitations of existing interface devices. While VR in this context has been introduced before by Chen et al. (CITE), the technology itself has advanced so dramatically since 2011 that it begets a new introduction wherein devices are much more consumer ready and hence have more potential for use in research and clinical environments. The immersive nature of VR/AR has the potential to keep abstractions closer to reality by making interaction ‘natural’ and reconstructing the whole brain environment for the user, potentially minimizing cognitive load. The combination acts in direct consequence to a note made by Margulies et al. [11], that the “*capacity of these [visualisations] to influence our interpretation of the data ... [is] worthy of careful consideration ... if we present a figure that clarifies the scientific content, but does so by creating a distortion of the brain space, is that bad practice?*”

In this paper, we present our ongoing work on fMRI visual analytics and explore the potential of immersive VR/AR. We anticipate that immersive representations will open up new opportunities primarily focused in:

- Displaying a higher level of connectivity in the network abstractions without increasing visual clutter
- Tighter coupling of the anatomy to abstraction for improved contextual awareness and reduced need for mental reconstruction
- Intuitive, natural navigation and interaction of the data and designs
- Improved ROI modelling of the brain regions under study, and
- Improved temporal exploration of longitudinal studies and time-series data

In the rest of the paper, we first present an overview of CereVA, a traditional mouse-and-keyboard interface for fMRI analysis that displays anatomical information adjacent to a visual abstraction. We then describe how VR/AR for immersive representations may be used on the components of the CereVA display, before exploring how VR/AR alters the concept of adjacency as it is currently used in CereVA. Finally we will highlight some exploratory work we have performed in the field of VR for medical data visualisation.

II. CEREVA: ADJACENT VOLUME RENDERING AND VISUAL ANALYTICS ABSTRACTION

The aim of the CereVA system was to link the positives of the 3D anatomical rendering with the benefits of an anatomically ordered network abstraction. The components of the interface are connected such that clicking on a node in the graphical abstraction highlights the related parts of the 3D brain representation for a user specified threshold. Similarly, a reverse mode, in which brain regions can be selected to highlight information on the graphical representation is available. Threshold selection guidance is enabled through an indicator that shows the relative number of edges for values within a correlation range. A heatmap view is also available to be used interchangeably with the

radial layout, and common graph statistics are available at a set threshold. See [15] for more detail. Fig. 1 shows an overview of the interface where a node has been selected on a thresholded radial layout such that the correlated regions are highlighted in red on the anatomical rendering. While the CereVA system provides advantages over single-mode visualisations, it still requires some mental juggling that we believe can be alleviated through an immersive VR/AR environment.

III. VISUALISATION COMPONENTS

There are two main visualisation components in CereVA as in Fig. 1: the anatomical rendering and the network abstraction. In this section we will describe how both components can be improved through VR/AR with regards to tighter coupling of the abstraction and the anatomy, reduced visual clutter, and potential reduction of cognitive load. We will also explore the ways in which VR/AR alters the interrelation of these components.

A. Direct volume rendering of 3D MRI data

Recently, the advent of efficient volume rendering algorithms and powerful graphical processing units (GPUs) has enabled direct volume rendering (DVR) of medical image data. This provides high-quality, interactive and flexible 3D visualisations of volumetric datasets. DVR has been demonstrated as an effective tool to visualise a variety of medical imaging modalities [19]. The main advantage of DVR over conventional surface volume rendering (used in Fig. 1) lies in the ability of DVR to allow a single visualisation to depict all the information within a volumetric dataset, which then allows for improved localisation of ROIs in relation to the adjacent regions.

In a previous study, we proposed an automated DVR method that produced visualisations where the adjacent regions can be maximally displayed while minimising the obtrusiveness to the visibility of an ROI [20]. We demonstrated potential benefits from the proposed visualisation, using multi-modality computed tomography and positron emission tomography (PET-CT), in terms of providing the visual correlation between ROIs and their related regions, and thus a rapid and precise means to understand the information in the data. The method does not require any modality-specific parameter and thus is also feasible for fMRI data. Fig. 2 shows the applicability of the DVR method to fMRI of brain. We can see that the correlation between selected functional nodes is effectively depicted.

By applying DVR with maximally visible ROIs within the volume-to-abstraction linking concept of CereVA, we can present the raw anatomical data in a way that meaningfully highlights ROIs while keeping as much anatomical context as possible. Providing this detail in an immersive VR/AR environment, we can link it to the abstraction in a natural, intuitive way that keeps the user's focus on recognising patterns in the data, rather than alternating their focus between the screen and a mouse or keyboard (CITE: Lee).

B. Visual analytics abstraction of fMRI data

Applying VR/AR to a flat 2D graphical abstraction does not provide much benefit over a traditional display. There are benefits in natural gesture-based interaction; however, to see the benefit of a HMD requires a more complex graph that plots into higher dimensions, or that interacts more directly with the volumetric data. As a result, this section first describes some potential avenues of innovation for the graphical abstraction that make use of a virtual environment, then it explores gesture-base navigation.

One of the more straightforward moves into 3D for the fMRI correlation data abstraction is to raise ROIs above the network. In this way, the anatomical ordering of nodes and edges is kept consistent, while the whole network contents can be reconfigured based on the relationship to the ROI node(s). This concept could be extended for specific combinations of characteristics, such as a correlation mapping of a set of ROI nodes on the 'top' network, mixed with a path-length constrained (from the ROI nodes)

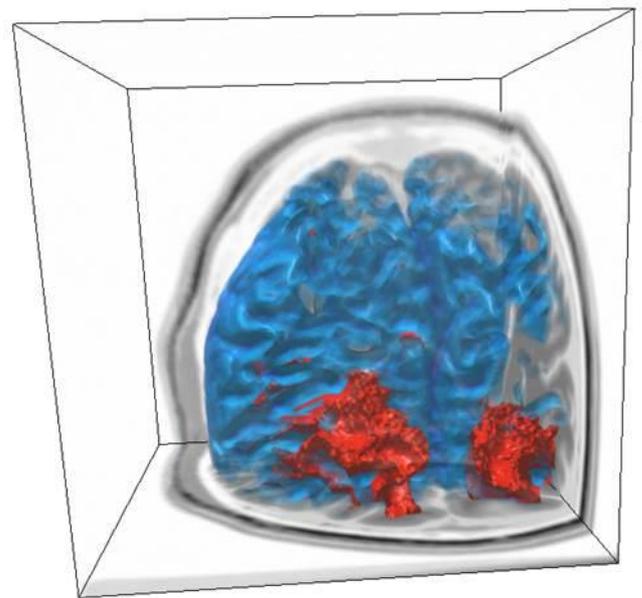


Fig. 2. Illustration of direct volume rendering of MRI data with segmented ROIs highlighted in red (frontal nodes of high correlation as selected by the user). The volume is also cropped (right and bottom) to better emphasize the ROIs.

abstraction on the 'bottom' network. As this can be viewed in a more immersive way than on a 'flat' screen, the increase in visual clutter can be minimised by moving 'within' the network, or by changing the viewing angle and interacting with natural gestures. These visualisation opportunities introduce an interface with more 'degrees-of-freedom' (CITE: Lee) as the data is not limited to a single, or group of, flat screen(s). By doing so, users are able to keep their attention on the data abstractions, thereby potentially allowing for a deeper understanding of the inherently complex information that progresses the field of fMRI analysis.

Another aspect that can be explored by moving the abstraction into 3D space is tighter coupling with the anatomical structure. Current methods of presenting the functional data in anatomical space, such as [12, 13], do so in a single surface or volume rendering. By moving the radial abstraction itself into 3D, it may be possible to move the anatomy onto the abstraction, rather than the other way around, such that more of the relevant anatomical information is displayed without the inherent clutter and implied pathways that limit existing methods.

C. Adjacency in virtual and augmented reality

When considering moving the CereVA interface into a VR/AR environment, e.g. with a 3D or 4D abstraction, it is not a straightforward task of keeping one component on the left and the other on the right. That is, the concept of adjacency in a VR/AR is much more fluid than it is on a ‘flat’ display, see Fig. 3 for a direct example. As briefly mentioned in the previous section, VR/AR presents opportunities for overlap between the anatomy and abstraction that don’t run into the same barriers of clutter and

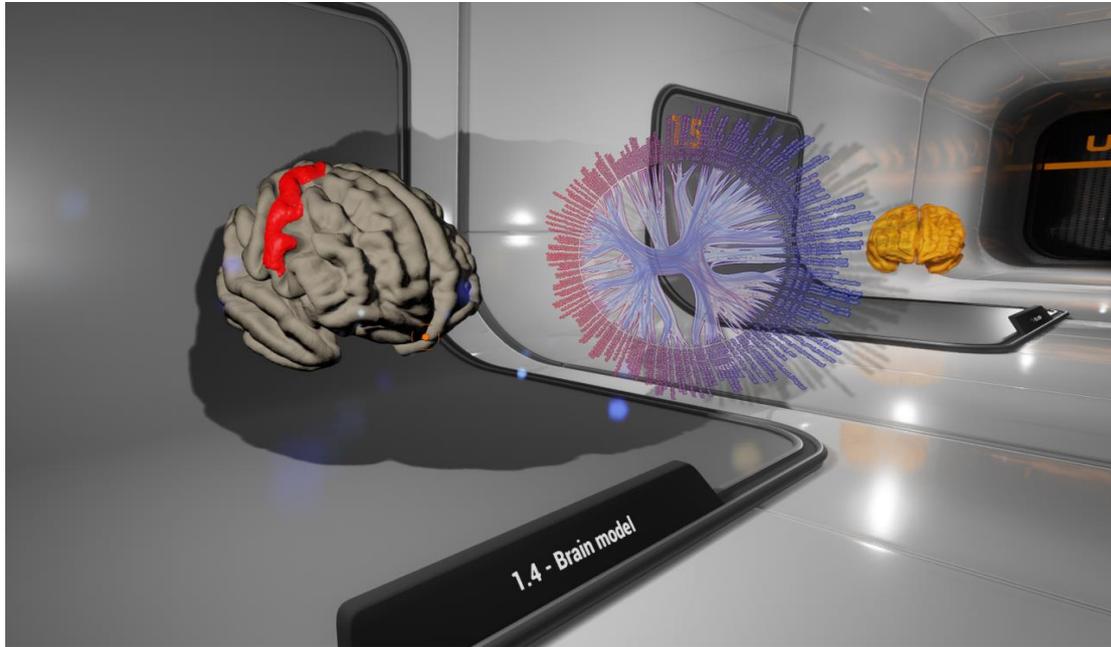


Fig. 3. An illustration of our ‘adjacency’ of volume rendering and visual analytics in a VR environment. While this is a simple example, it illustrates the possibilities for stronger interlinking and a fluid concept of adjacency. The brain on the left has an ROI highlighted in red that corresponds to a node on the abstraction. The radial graph on the right is similar to that in CereVA, showing the correlation between brain regions at a user defined threshold. The brain in the background represents the next time-point in a temporal set of scans, or another subject that can be compared. Moving around in the scene could highlight similarities and differences on the radial in the middle. The background in this image is simply for illustrative purposes, and could be made to display content relevant to the visual analysis to the fMRI data.

Finally, as fMRI studies are often longitudinal, such as following the changes in dementia, or pre-and post-onset of schizophrenia, there is a need to explore moving abstractions into a higher, fourth dimension. With a traditional display, this may have been performed by scrolling along a timeline, or use of animation to show the changes in the fMRI correlation data. With VR/AR, while the fourth dimension itself is not ‘visible’, the interaction with a timeline can be made more intuitive through the use of gestures. Moreover, the example approaches of moving into 3D can be combined with the temporal component to present more data with less clutter at each time point.

These suggestions for moving the abstraction into 3D and 4D such that the benefits of VR/AR can be realised are among many other possible applications. To fully utilise the power of immersive VR/AR for fMRI visualisation, innovative exploration will need to be undertaken and examined by end users, such as researchers and clinicians, for their applicability and potential in improving fMRI analysis.

implied pathways of current displays. While it is not an advanced implementation, Fig. 4 illustrates the basics of this concept. Moreover, the ability to rearrange and take elements from one ‘half’ of the interface and plug them into the other ‘half’ are introduced with natural gesture-based interaction. Similarly, the ability to use physical objects and props alongside renderings in AR presents unique opportunities that can be used to minimise visual clutter and maximise natural interaction with the data. These are discussed in the following section. Therefore, by moving into a VR/AR environment, the concept of adjacency and the linking between components needs to become more advanced,

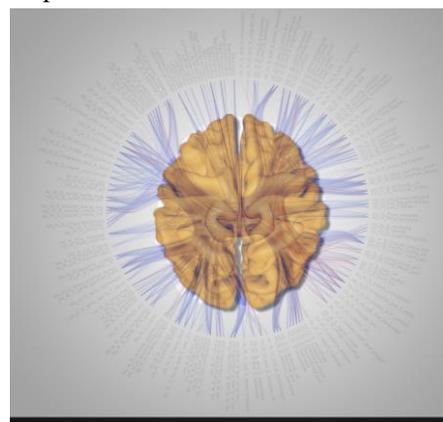


Fig. 4. With moving the abstraction into a 3D environment, opportunities arise to present the anatomy and the abstraction together without the implied pathways of current methods. This figure, while it does still imply pathways, illustrates the basics of the concept of moving the radial abstraction into 3D with the anatomy.

presenting many opportunities for a natural feeling interface that allows users to focus on the data rather than how they are interacting with the data.

We believe that, as this is a new class of problem that has not been encountered before, it will require a large amount of experimentation. Inspiration may be available from the process of moving from data reports to dashboards in a range of industries, as well as how data are presented in games, where people have long acted as a character within a virtual environment. One possible technique, for VR, when considering these two inspirations is having a core ‘field-of-view’ with an overview of the information that can be manipulated to add or remove parts, e.g. nodes/brain regions. Then, stored just outside the ‘field-of-view’, modules can be added to the central display and dragged into position such that they click in to meaningful positions that reduce clutter, much like a jigsaw puzzle. Meanwhile AR can further this concept by being able to physically move objects into and out of scene, or flip a page upon which a rendering is projected to remove it from the scene.

D. Data interaction in virtual and augmented reality

Since the 1990’s, there has been discussion about how to make interfaces as ‘invisible as possible’, a concept that relies on creating ‘natural’ forms of interaction (CITE: Lee). Current displays, however, are limited in how well they can mimic natural gestures. For example, the action of clicking and dragging on a mouse, or a touch-enabled screen, to move an icon is an attempt to mimic the action of picking up an object to move it. While the action contains the key elements of the physical gesture – create contact with object, move object, release object – it still has a wide remove between the person and the technology. Both VR and AR have the potential to shrink this gap by transform interaction with, and navigation of, scientific data, such as fMRI.

Considering VR first, gesture recognition devices, such as the Leap Motion controller, and the Microsoft Kinect, can be used in conjunction with HMDs such that hand and body motions cause changes to occur in the data visualisations. In the context of CereVA and adjacency, this may mean grabbing and lifting nodes in the network abstraction to cause changes, such as those mentioned in the previous section. Similarly, brain ROIs in the atlas could be selected, altered and/or removed from the display with gestures. Furthermore, changing the style of network abstraction, brain atlas and even subjects being viewed could be performed through voice commands or a set of gestures, e.g. filing the data like a report. These suggested techniques address well known pitfalls of current displays and interaction methods, such as reducing the need for menus that ‘drown users in functionality’, and limitations of interacting with 3D data on a 2D screen (CITE: Lee). They do, however, introduce their own issues of having no haptic feedback, and limited visual feedback as the users cannot see themselves.

While there are some techniques available that introduce haptic and visual feedback, including rendering body parts, and gloves with mimicked physical resistance, these are only a facsimile of real interaction. AR takes the philosophy of

natural interaction one step further. By introducing rendered objects to a real-world viewpoint, AR can make use of fully natural interaction, such as picking up objects, moving them around, tracing an outline, or folding an object. This creates an even stronger sense of being present with the data as information, e.g. DVR content, can be projected directly only a physical prop of a brain. The issues that arise here lie mostly in the fact that less research has been performed into AR than VR and haptic devices. Therefore concepts such as this projection are in a relatively infantile state. Moreover, while a user can ‘feel’ a physical prop, they cannot ‘feel’ the renderings around the prop, and similarly may ‘feel’ objects as different to what they see, e.g. if a DVR is showing a slice halfway through a brain prop, it looks like only half the brain is there, meanwhile the user is still holding the whole brain. Neither VR nor AR is a perfect solution, especially at this point of development, yet both techniques have the potential to be leaps and bounds ahead of current mouse, keyboard and touch methods of interaction. As espoused by Lee et al. (CITE: Lee), “No matter how simple and easy-to-use an interface is, there is always a gap (i.e., indirection) between a person and the technology.” It is the reduction of this gap that matters in scientific development whereby it may, “offer (sic) more power to explore data visually.”

IV. EXPLORATORY VISUALISATION

This section highlights two pieces of exploratory research we have performed that will guide us in applying VR, and AR, to fMRI visual analysis. This first is using a HMD for rendering the anatomy of the brain in VR, and the second is using gesture-based input to navigate a 3D medical data environment.

A. Oculus Rift brain rendering

Fig. 5 presents our exploratory work on the use of Oculus Rift to visualise the MRI volume data in a fully virtual environment. Data rendered through our VR application is capable of providing real time interaction at 25-40 fps (on an AMD Radeon 6970 Crossfire GPU) between the user and the generated models. We provide the user freedom to view and interact with the models from any angle or perspective. This exploratory work mimics the brain rendering part of CereVA in that specific ROIs can be highlighted on a user’s command and a dummy signal is sent as though it were linked to the graphical abstraction. By combining our VR application with gesture-based input, such as is presented below, we may enable natural user interaction that can reduce the cognitive load of performing tasks auxiliary to analysing the data.

B. Leap Motion Medical Graphical Avatar

The Medical Graphical Avatar (MGA) is a system that displays Personal Health Record multimedia in a WebGL-based environment [21].

In our explor

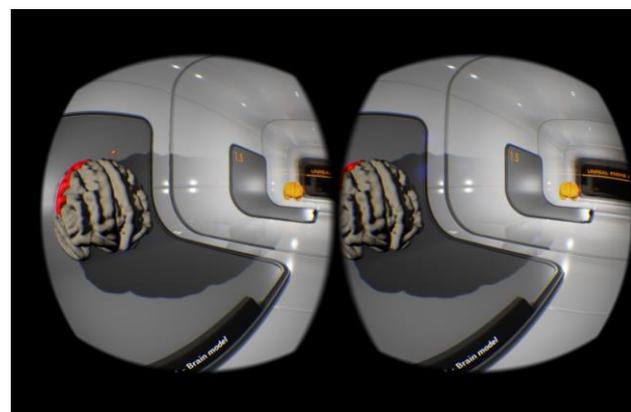


Fig. 5. ROI highlighting in the Oculus Rift virtual reality environment.

atory work with MGA, we developed a set of navigational gestures using the Leap Motion controller [22]. The gestures enabled common tasks in the system, such as stepping through events on a timeline, play/pause of medical video, moving forward/backward in medical image stacks and rotating/panning in the scene. In our experimentation, we measured the accuracy of the controller in recognising the gestures and found an average of 83% accuracy across the gestures. Since the publication, the Leap Motion controller and software has undergone multiple iterations leading to a more natural interaction. It is now possible to mount a Leap Motion controller on an Oculus Rift HMD such that gestures are used as navigational input. As a result, gesture-based input can be used to reduce the cognitive load of analysing fMRI visualisations by allowing users to keep their focus on the data and designs, rather than how they are interacting with the objects in the display.

V. DISCUSSION AND OUTLOOK

The potential for visualising and analysing complex fMRI data in an immersive VR/AR environment is only starting to be researched and understood. In this paper we suggest some avenues that can be explored in the domain. Our suggestions are based on the complex interplay of visualising meaningful functional correlation abstractions while also retaining the inherent anatomical context. With this, the key components of mental reconstruction, visual clutter and potentially misleading information, i.e. implied pathways, are considered at each stage. We therefore present VR/AR as a potential tool in creating visualisations that “clarify the scientific content” without “creating a distortion of the brain space” [11] in fMRI data analysis.

There are several challenges that need to be addressed, however, for broader application of VR/AR and gesture-based navigation for fMRI data visualisation and analysis. Many of these apply to known limitations of the technology, which include, symptoms of motion sickness and strains placed on the ocular system, HMDs with a limited field of view, gesture-based navigation devices having inadequate robustness, and the problems of latency and poor registration of projections in AR. A lack of standard protocols and regulations in VR/AR devices/software is another concern. Fortunately, many of these challenges will be overcome as devices improve and companies work together, e.g. as Oculus and Leap Motion have for the Leap Motion controller mount.

For fMRI data, two specific challenges of note are: first, ensuring gesture-based navigation methods are aware and responsive to the variability in the data, i.e. anatomy navigation, compared to graphical abstraction navigation, compared to time-series and temporal abstraction navigation; and second, while VR/AR has the potential to reduce clutter through updated concepts of abstraction and adjacency, there is also the potential for it to do the opposite and increase the amount of information in the visual field. Research in this area that is cognizant of these challenges, and many others faced by existing fMRI analysis techniques, has the potential to revolutionise the field and *illuminate* profound

understanding of the complex data at the final frontier of modern medical research.

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