

The Human Brain Project – Chances and Challenges for Cognitive Systems

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Abstract: The Human Brain Project is one of the largest scientific initiatives dedicated to the research of the human brain worldwide. Over 80 research groups from a broad variety of scientific areas, such as neuroscience, simulation science, high performance computing, robotics, and visualization work together in this European research initiative. This work at hand will identify certain chances and challenges for cognitive systems engineering resulting from the HBP research activities. Beside the main goal of the HBP gathering deeper insights into the structure and function of the human brain, cognitive system research can directly benefit from the creation of cognitive architectures, the simulation of neural networks, and the application of these in context of (neuro-)robotics. Nevertheless, challenges arise regarding the utilization and transformation of these research results for cognitive systems, which will be discussed in this paper. Tools necessary to cope with these challenges are visualization techniques helping to understand and gain insights into complex data. Therefore, this paper presents a set of visualization techniques developed at the Virtual Reality Group at the RWTH Aachen University.

1. INTRODUCTION

The main goal of the Human Brain Project (HBP) is “to build a completely new ICT [(Information and Communication Technology)] infrastructure for neuroscience, and for brain-related research in medicine and computing, catalyzing a global effort to understand the human brain and its diseases and ultimately to emulate its computational capabilities” (The HBP, 2013, p. 3). To reach this ambitious goal, around 80 European research groups contribute to the project working together in various subprojects. They are facing challenges of gathering, handling, and making available vast amounts of data and applying analysis tools on it. Furthermore, researchers are challenged by the generation and simulation of brain models, and finally by bringing results to a variety of applications in medicine and brain research. The highly interdisciplinary mixture of researchers from neuroscience, computer science, physics, medicine, and philosophy offers a great chance to merge expert knowledge of different disciplines for brain research.

In context of these goals and efforts in the HBP, various chances can be identified regarding cognitive systems research. The list below gives a brief review of possible chances. It should be noted that this work does not intend to identify possible gaps in the research field of cognitive systems and therefore, will not clarify how these gaps can be filled by means of results emerging from the HBP.

- *Understanding the human brain:* One central objective of the HBP is to significantly deepen the understanding of the human brain. Cognitive systems research can directly benefit from insights into the structure and function of the human brain by applying these to extend and refine concepts used

for the creation and the implementation of intelligent system components and cognitive controlling mechanisms.

- *Brain simulation:* A variety of simulation approaches and algorithms exists for simulating neural structures and functions, e.g., implemented in the NEST (Diesmann *et al.*, 2001) or Neuron (Markram, 2006) codes. The main objective of these approaches is to simulate the neural structure and function of small regions in an animal or human brain to gain deeper insights into its emergent behavior. Another application for these simulations can be found in cognitive system implementations, as focused on in the next passage.
- *Application to technical systems:* As an individual subproject of the HBP, it is planned to use simulated neural networks as “intelligent” component for robotic systems by sending sensory stimuli to the network simulation and retrieve output from it redirected to actuators of the robot. This research has a high potential to generate results that can directly be applied to cognitive systems in general.

To make these findings accessible to cognitive systems engineering, the results coming from the HBP have to be transformed and integrated into existing concepts, tools, and implementations used in this discipline. Only by coping with this major challenge, research results from the HBP can be successfully used in cognitive systems engineering and leverage the high potential of brain research in this context. This work discusses these issues in more detail and tries to identify certain requirements and concepts offering solutions to this integration problem. In this context, visualization techniques are one of various promising tool solutions

Tab. 1: Sub projects of the Human Brain Project

SP1	Strategic Mouse Brain Data
SP2	Strategic Human Brain Data
SP3	Cognitive Architectures
SP4	Mathematical and Theoretical Foundations of Brain Research
SP5	Neuroinformatics
SP6	Brain Simulation
SP7	High Performance Computing
SP8	Medical Informatics
SP9	Neuromorphic Computing
SP10	Neurorobotics
SP11	Applications
SP12	Ethics and Society
SP13	Management

supporting this transformation and integration task. Therefore, scientific visualization approaches are capable of reducing the complexity to understand models and data, and thereby making the results accessible for cognitive systems engineers.

This work is structured as follows. Section 2 will discuss the introduced changes in more detail focusing on further related work and a closer look to current research activities in the HBP. Section 3 will focus on visualization techniques and tools developed in the Virtual Reality Group at RWTH Aachen University, especially in the focus of scientific visualization of neural experimental and simulation data. These tools are on one hand an integral part of the HBP and on the other, are used for working with the above mentioned data. Furthermore, these tools cope with the transformation and integration challenge for cognitive systems research as discussed above. Section 4 will summarize the discussed aspects and catalyze indications for research on cognitive systems.

2. CHANCES AND CHALLENGES

The main objective of the HBP is to create a platform containing data sources and tools supporting the research process to understand the human brain. Here, the structure and function of the human brain are two major foci of ongoing investigation. Both aspects are essential for human cognition and possible outcomes are of interest for various related research fields like medicine, computer science and system engineering, etc. Understanding the function of human cognition on a functional level could make these extractable for system engineering purposes and so can directly benefit to cognitive system research.

The HBP is generally structured into 13 sub-projects (SP), as listed in Table 1. SP 1-3, 5 and 8 mainly concentrate on data generation and organization, SP 4 migrates research on theoretical foundations of brain research, SP 6 and 7 focus on brain simulation and high performance computing, SP 9 develops a neuromorphic computing platform, which focus on rebuilding neural structures in silicon-based hardware chips. SP 10 integrates research results from other SPs into a neurorobotics simulation platform, which relates this SP very

close to cognitive systems engineering. Finally, SP 11 discusses applications and SP 12 concentrates on ethics and society in context of HBP. SP 13 is meant to handle the entire management processes of the project.

Cognitive System research can mainly benefit from data acquisition and from data organization sub-projects as well as sub-projects concentrating on brain simulation and neurorobotics. The latter sub-projects combine results from cognitive architectures, models of the human brain, and brain simulation as cognitive system generally do.

SP 1 and 2 mainly concentrate on data generation and integration, resulting from experiments involving the human and mouse brain. Results from these experiments are incorporated into models of the brain describing its structure and function. A model based abstraction of these findings is assembled in context of work done in the SP 3 creating cognitive architectures. This offers great chances for cognitive system research regarding the development of new system concepts and intelligent controlling implementations.

Nevertheless, various types of data are generated and have to be integrated and interpreted to derive the targeted abstraction and research results. First of all, structural data in form of brain atlases are produced. For instance, the JuBrain Atlas (The JuBrain Project, 2014) contains cytoarchitectural probabilistic maps that were gained by analyzing histological sections of post-mortem brains (Zilles *et al.*, 2002, & Amunts *et al.*, 2007). The Big Brain (Amunts *et al.*, 2013) is a recently developed tool for accessing anatomical data at a resolution of 20 micrometers that allows for new analysis of the structural and spatial organization of the brain. Beside these atlases, brains are acquired post-mortem to gain high resolution images with information on nerve fiber tracts. Polarized Light Imaging (PLI) is an imaging technique that enables the identification of the structure and direction of nerve fibers in brain slices (Axer *et al.*, 2011a, b). Finally, data is derived from recording local field potential (LFP) of monkeys' visual cortex while they are performing visual tasks (Ito *et al.*, 2013).

As mentioned above, this experimental and data-driven view on the HBP brings up the challenge of making these results accessible to cognitive system research. On one hand, visualization techniques can be used, as further discussed in Section 3 below. On the other, research done on neuroscientific simulation comes into place. SP 6 entitled "Brain Simulation" concentrates on research and modeling of the human brain's structure and function using mathematical and algorithmic simulation models. There are various approaches to model and simulate neural structures and their functionality. Neuron (Markram, 2006) is a simulator that concentrates on a small set of neurons in more detail (on a chemical level), while the NEST simulator (Diesmann *et al.*, 2001) focuses on very large networks by simplifying the description of single neurons. NEST concentrates on the dynamics, size, and structure of neural systems. The result of a NEST simulation is spiking data describing the firing of single neurons at specific points in time. Main challenge for cognitive systems research here is to integrate these approaches into cognitive systems. Nevertheless, SP 10

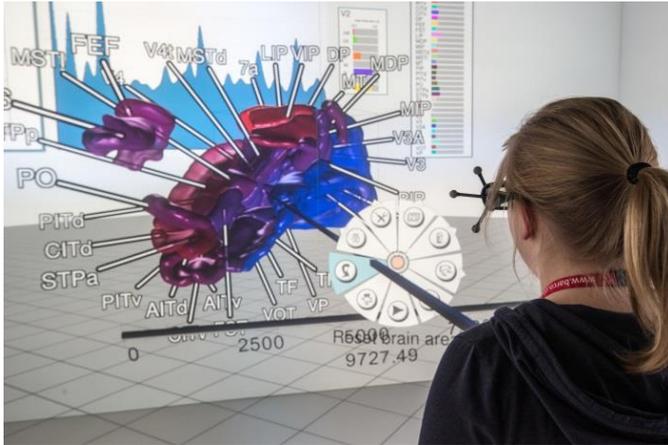


Fig. 1: Left: A researcher is inspecting a simulation run in a CAVE. While interacting with pie menus the user can control the visualization. Right: The user is studying the dynamics of information exchange between brain regions.

develops certain approaches for using simulation techniques in context of technical systems.

Thus, SP 10 is one example of a direct consumer of results from HBP's research efforts. Main goal of SP 10 is to develop a simulation of robots in a virtual environment that is based on simplified brain models resulting from the HBP research. Beside function and structure of human brains, also cognitive architectures play a central role as modeled and developed in SP 3 entitled "Cognitive Architectures". Thus, the combination of simulated neurorobots, simplified brain models, and cognitive architectures can be of great benefit for cognitive system research. Nevertheless, main challenge in this context is the transfer of these results into cognitive system research by abstracting neuroscientific research results.

As one key technology for enabling cognitive systems researchers to integrate knowledge from experimental brain research, models and techniques, the following section focuses on visualization concepts and tools developed by the Virtual Reality Group at the RWTH Aachen University. These concepts and tools are developed to support the neuroscientific work undertaken in the HBP as well as to enable scientists to gain insights into the complex models and data produced.

3. VISUALIZATION AND INTERACTIVE SUPERCOMPUTING

The Virtual Reality Group at RWTH Aachen University is part of the HBP and cooperates closely with the Forschungszentrum Jülich on the topics of scientific visualization and interactive supercomputing. The central goal of our research in the context of the HBP is to develop highly scalable scientific visualizations, such as demonstrated in the VisNEST prototype (Nowke et al., 2013), described in more detail in Section 3.1, volume rendering associated to degenerative brain data (Hänel et al., 2014), sophisticated graph visualization applications using edge bundling, and in multi-view and multi-device scenarios offering scientific

provenance tracking for neuroscientists. Volume rendering refers to a class of visualization algorithms, which mainly address the visualization of 3D volumetric data that is generated by, e.g., MRI or CT imaging techniques. Section 3.2 will discuss a specific use case for volume rendering, which shows the relevance of these techniques in context of brain research.

Graph visualization methods are a means to generate visual representations of relation data, e.g., the connectivity of brain areas. In most cases, graphs are visualized as node-link diagrams, where nodes are visually represented as dots and links as lines connecting these dots. In brain research, spatial structures are of interest, which deem 3D graph visualization in many cases relevant. Section 3.4 will point out this aspect in more detail. Finally, scientific provenance tracking aims at making data generation and processing persistent and thereby reproducible.

We are targeting highly immersive Virtual Reality and high resolution display settings as possible application and production environments. As mentioned above, the visualization as well as the interpretation of 3D spatial data is of central interest in brain research. Immersive Virtual Reality techniques offer 3D stereoscopic rendering capabilities as well as a variety of interaction methods and tools to interact with these visualizations. This offers a distinct quality of scientific work with data than it is possible with standard workstation equipment. Section 3.3 introduces a tool for the visualization of high resolution data. For this use case, high resolution visualization infrastructure is of main interest.

Our technologies are planned to be part of a concept for interactive supercomputing, as an essential part of the HBP. Interactive supercomputing addresses the problem of data transferring costs and the steering of simulations on high performance computing infrastructure. The overall goal thereby is to transfer visualization to the data generation process during simulation runtime and therefore enable scientists to steer these simulations which is impossible with

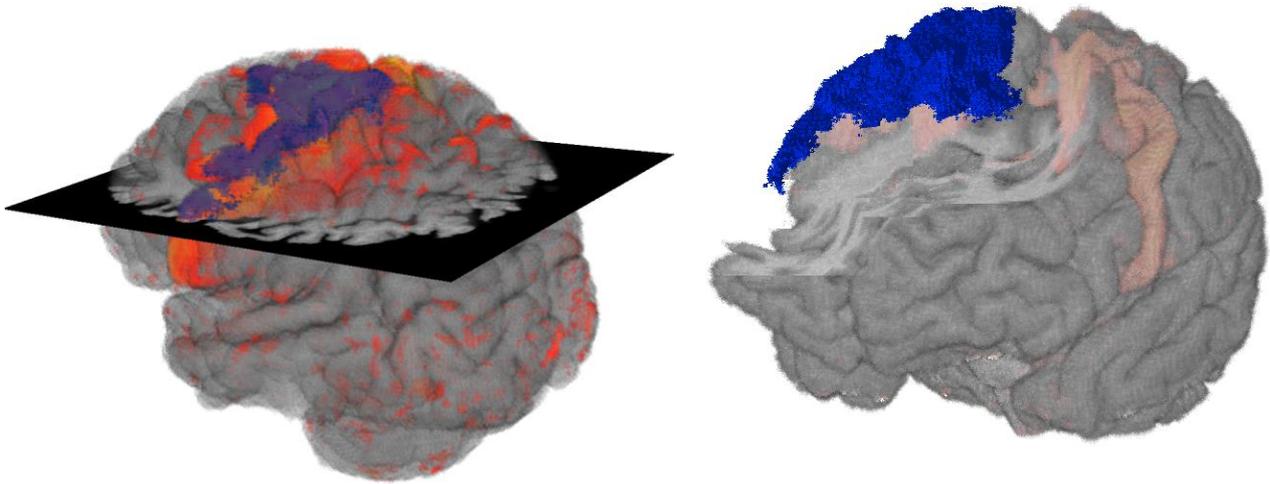


Fig. 2: Left: The semi-transparent anatomy is combined in one volume rendering with degenerative data (red to yellow) and the premotor cortex (blue). The anatomical section additionally supports the spatial orientation. Right: A view-dependent cutout is created around the premotor cortex to allow for a detailed examination of surrounding structures.

current system architectures. Finally, all tools and visualization concepts developed in the Virtual Reality Group will directly contribute to the previously discussed research topics and will likely be key enabler for neuroscientific research. The following subsections will give a deeper insight into the current developments in the group and show its contributions to the research efforts in the HBP.

3.1 VisNEST

The simulation of large spiking neural network models generates an unprecedented amount of data that has to be analyzed to understand the dynamics and properties of these networks. While most researchers visualize their data in a non-interactive fashion, sophisticated visualization systems tailored to quickly verify or reject a specific hypothesis on the simulation data can have great impact on the researcher's time spent to study the simulated neural network. In addition, data exploration often involves constructing a mental model of the simulation to identify features of interest. To this end, we developed VisNEST, a visualization tool specifically build to visualize simulation results from modeling the visual cortex of a Macaque monkey. One driving challenge behind this work is the integration of macroscopic data at the level of brain regions with microscopic simulation results such as the spiking behavior of a single neuron. VisNEST primarily offers four distinct views to inspect this simulation data. Each view highlights certain aspects of the simulation.

The first view is designed to give neuroscientists a first impression of the entire simulation run. To do so, we render brain regions of the visual cortex and map their respective neural activity by means of color coding each region (cf. Fig. 1 left). As neural activity, we define and calculate the mean firing rate of all neurons inside a region. Interaction with the system is primarily mapped to pie menus, beside some

control elements like the time slider, which allows for browsing through simulation time. This approach allows for scaling the visualizer from desktop workstations to CAVE-like environments, since interaction among the system stays consistent.

A CAVE is a computer generated immersive virtual environment in which a user can interact with her natural senses. Immersion is achieved through stereopsis which basically works by generating images for each eye. These images are rendered from the perspective of each eye. Through a filter process, each eye perceives only its corresponding image, thus creating a sensation of depth. One important aspect offered by CAVEs is the possibility to use natural interaction, hence lowering the mental load of the user, permitting to concentrate more on the brain simulation data set in context of VisNEST. In a CAVE, a user can point at a brain region of interest using a tracked input device. The system then automatically displays its corresponding activity as a function-plot over time, shows the raster plot of firing neurons, and depicts the individual activity of populations. Each brain region is built of populations which on their part define a set of neurons that constitute this population.

The second view depicts the hierarchy used for simulation of brain regions and shows the connectivity within populations. In this view researchers can see how activity is cascading and spreading along the simulated brain regions. Inspecting the connectivity of brain regions is provided by the third view. To this end, a fixed graph node layout is used where connections are depicted by arrows. The thickness of arrows is used to convey the connection strength between regions. The last view offers a visualization design to depict the dynamics of neural activity projected to brain regions (cf. Fig. 1 right). This approach can help to obtain an impression of how information is exchanged between regions. Conceptually, this view is similar to the previous one but

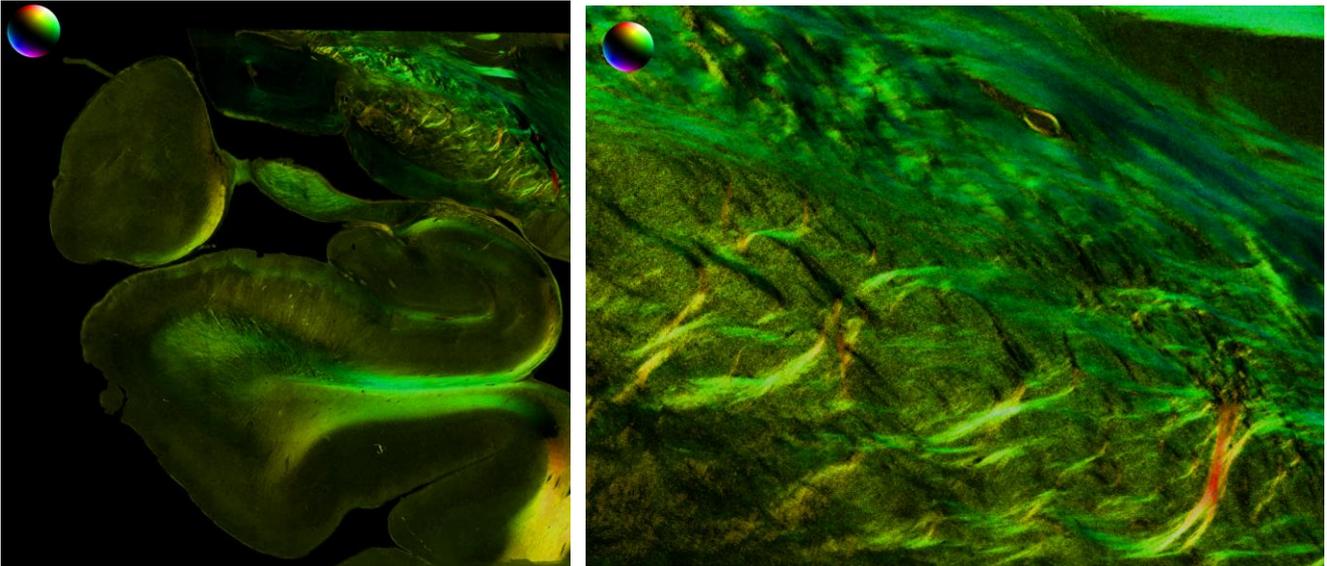


Fig. 3: PLI section color-coded corresponding to the sphere in the upper left corner. Right: High zoom level to gain benefits from the high resolution. Left: Overview visualization of the hippocampus.

instead encodes the dynamics of information exchange dynamically to arrow thickness.

The visualization application is being developed in close collaboration with domain scientists. This approach requires constant reevaluation of the current system to assure its usability and integration to the current workflow of neuroscientists. In the near future, we will face the challenge to directly link the visualizer to the above discussed neural simulator NEST in order to steer the simulation and directly assess the impact on the network. In addition, we will need to store a variety of data modalities, be it raw spiking data, derived statistical quantities like information exchange, or geometry data. A unifying middleware for storing and accessing this data while considering latency constraints is required and aspect of future work.

3.2 Volume rendering of combined data sets

The JuBrain Atlas (The JUBrain Project, 2014) contains probabilistic maps of cytoarchitectural regions that can be registered onto other acquired brains. Thus, they are also used for analyzing the evolution of a brain degenerating disease called corticobasal syndrome. According to this mapping, it can be statistically analyzed to what extent a certain brain area is affected. However, this data is commonly visualized by rendering it as 2D sections for gaining deeper insights into it. This reduction of three dimensional data to two dimensions affects the spatial perception of extent and location of the degeneration.

Therefore, we implemented two approaches for a 3D visualization of anatomy, degeneration data, and brain regions to undergo various problems arising from the classic 2D visualization. On the one hand, the degeneration happens not only on the surface of the brain so that a surface visualization is not sufficient. On the other hand, the surface

contours are necessary for a better spatial orientation for a user who interprets the data.

The first visualization design combines a common 2D anatomy section with the volume rendered data sets (see Fig. 2 left). The anatomy is integrated as a semi-transparent volume and the degeneration data are opaque. The brain areas can be adjusted in their opacity to give an individually blended view onto degeneration that may be located inside of the visualized brain. This view can be controlled by pie menus, as has been discussed above.

In comparison to the first design, the second one allows for a more detailed inspection. Here, one or multiple brain areas are determined as the volume of interest (VOI), which is supposed to be visible from all points of view. Therefore, a conical cutout is created around the VOI and always stays aligned to the viewer (see Fig. 2 right). In this design, the anatomy is opaque and, thus, is the part to be clipped. On the cutting surface, anatomical data is shown to estimate a spatial orientation and depth. The user can influence the rendering of the degeneration data in the cutout. The enlargement or reduction of the cutout that is shaped like the VOI allows the user to set the desired amount of context information.

The application combining these two visualization designs is available for desktop and immersive setups. As shown in (Laha *et al.*, 2013), the depth perception and estimation in volume data is improved in immersive setups and in our case enhances easier differentiation of the combined data sets.

3.3 PLI visualization

Polarized light imaging is a recently developed technique for the acquisition of fiber tracts at a very high resolution (Axer *et al.*, 2011a, b). Nerve fibers are surrounded by a myelin sheath that shows a uniaxial double refraction. When thin brain slices are shined through with polarized light, this

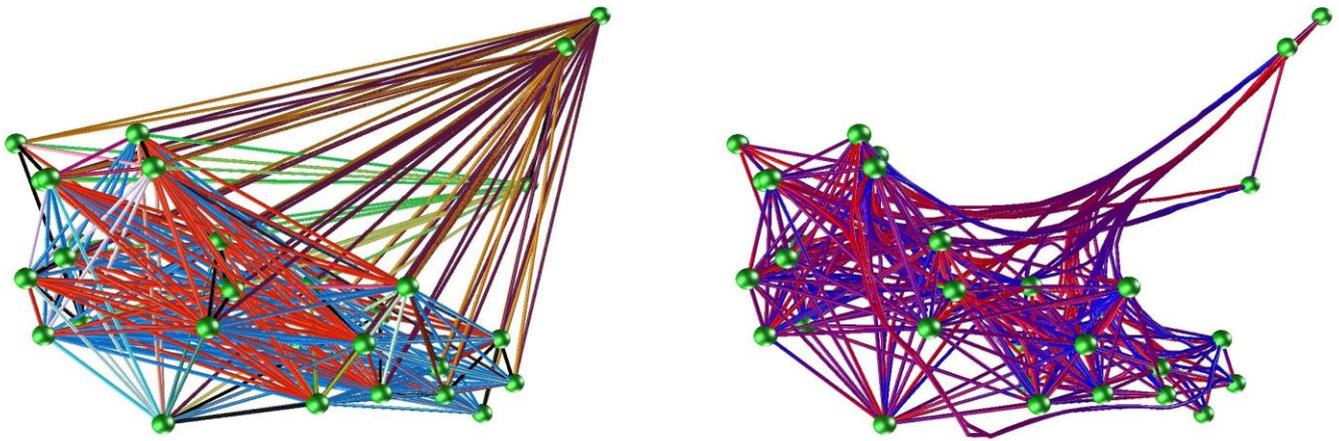


Fig. 4: Node-link diagram of an almost fully connected, bidirectional graph, originating from a simulation of point neurons. This images depicts 32 nodes each of which resembles a brain region. The edges are the regions' interconnectivity, whose weights are not considered here. Left: original graph shown with 27 color-coded clusters consisting of similar edges; black edges are unclustered, i.e., not similar to any other. Right: the same graph after edge bundling; the edges are directed from blue to red.

property evokes an optical anisotropy and corresponds to the spatial orientation of the fibers. PLI images have a resolution of down to 2 micrometers, and thus allow for a data analysis at a nearly single nerve level as nerve fibers have a diameter of about 0.1-22 micrometers. With techniques like diffusion tensor imaging only much larger fiber tracts can be approximated. The high resolution of PLI data facilitates to gain new knowledge about the spatial distributions of fibers.

However, an interactive visualization of data with this resolution is challenging. Next to the 3D reconstructed PLI image stack, an anatomical data set at a lower resolution is available leading to an overall data size of about 1 terabyte or more. Therefore, advanced memory and visualization techniques need to be applied, as for example introduced by (Fogal *et al.*, 2013) and (Hadwiger *et al.*, 2013). Here, the volume is divided into bricks, and due to a virtual memory hierarchy only visible parts of the volume at multiple resolutions are loaded into the GPU, which then can be displayed with a high frame rate. If the user zooms out or wants to rotate the volume and not all needed data blocks are already loaded into the GPU, a request to the data storage is sent. This limits the in- and output data stream to a minimum, that is known to be a bottle neck of implementations like this.

For PLI data, we want to further improve these approaches with special consideration of displaying them in a virtual environment. For a better immersive feeling in such an environment, head tracking in combination with a user-centered projection is used. This leads to a permanent update of the view position and therefore to missing data blocks on the GPU. It needs to be explored how this affects the frame rate and the fluency of interaction. In addition, switching between different levels of detail may also lead to the so called cyber sickness.

A first visualization is shown in Fig. 3. Here, mipmaps of one brain section are pre-calculated to allow for an interactive visualization. The fiber direction is color-coded in the HSV color space, while the orientation of the space can be adjusted to highlight fibers.

3.4 Interactive 3D graph visualization

Graphs have turned out to be an important data structure in computer-supported brain research, which can also be seen in the above described VisNEST application. Networks of neurons in the brain can be identified on the microscopic scale and linking of whole brain regions on the macroscopic scale. Furthermore, graphs are an essential tool for visual analytics, for example in correlation analysis.

We are concentrating on the visualization of graphs in node-link representation regarding their intuitiveness and addressing the challenge of reducing visual clutter. While 2D graph visualization is very common and represents a broad field of past and current research (van Landsberger *et al.*, 2011), 3D graph visualization is not that wide covered. Still, adding the third dimension to graph visualization approaches is especially interesting for spatial data like the interaction of cortical regions in a human or animal brain. Additionally, exploration and analysis of non-place-bound graphs can benefit from 3D layout and visualization in particular in an immersive environment (Ware *et al.*, 2008). Especially the latter allows interactively working on larger graphs while keeping the same precision, respectively error rate, of interaction in typical tasks, such as following paths in a given graph (see Figure 4).

As mentioned above, drawing larger graphs as node-link diagrams quickly leads to heavy visual clutter caused by edge crossings. This problem is particularly relevant for dense

graphs as formed by neurons. Edge bundling is one technique tackling this problem by partially drawing nearby edges as a single one. To decide which edges are bundled and which are not, versatile metrics are applied that differ in their results, for instance in the ratio of information loss to clutter reduction, cf. (Lou *et al.*, 2012, & Holten *et al.*, 2009). One of our goals is to extend this technique to 3D and in addition to let the user influence the edge layout process, as well as interactively change the underlying metrics.

A second method used to reduce the visual cluttering of node-link diagrams is rearranging vertices to reduce edge crossings. Many existing approaches use a system of spring forces for this purpose (Fruchterman *et al.*, 1991, & Walshaw, 2003). Nevertheless, spatial data that is visualized as node-link diagram is excluded from these approaches according to the applied change of vertex positions, which is data inherent. Thus, in the moment vertex positions get changed the visualization does not represent the data correctly. Similar to the edge bundling approach, we want to involve the user into this process by allowing her to interactively manipulate the resulting graph layout by means of a continuous force equilibrium. Thus, this algorithm differs from the classic algorithms that use a cooling factor for stabilization and termination. In this approach, it is much more challenging to stabilize the continuous computation in terms of overreacting forces. Nevertheless, in the focus of interactive graph visualization, this approach shows better runtime behavior because every user initiated change does not cause a re-computation of the graph layout.

We want to investigate clustering (Balzer *et al.*, 2007), interactive graph operations, and session management as further topics in interactive 3D graph visualization. Clustering reduces clutter while the other approaches focus on supporting the analyst in understanding and exploring graphical structures. Thus, methods of visual analytics have to be applied to the underlying data to gain further insights, which requires operations on the graphical data and in turn can change its representation.

4. DISCUSSION AND FUTURE WORK

In conclusion, the above presented work shows various aspects of possible outcomes and chances for cognitive systems research and potential ways how to gather relevant results out of the HBP, e.g., by using visualization tools and techniques. Especially the work on neural simulators make neural models accessible for cognitive systems research. Furthermore, their application in neurorobotics and the creation of cognitive architectures are candidates to directly offering results to cognitive systems research, especially due to the close relation of the neurorobotics research to cognitive systems engineering.

Future work should consider the question how to integrate results from the HBP into cognitive systems research and how cognitive systems can directly benefit from these results. Therefore, in a first step existing research gaps in cognitive research should be identified. Afterwards, concepts and results from the HBP w.r.t. their use in cognitive systems

should be examined, implemented and finally transferred to relevant system architectures.

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