Self-portraits of the brain: cognitive science, data visualization, and communicating brain structure and function

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With several large-scale human brain projects currently underway and a range of neuroimaging techniques growing in availability to researchers, the amount and diversity of data relevant for understanding the human brain is increasing rapidly. A complete understanding of the brain must incorporate information about 3D neural location, activity, timing, and task. Data mining, high-performance computing, and visualization can serve as tools that augment human intellect; however, the resulting visualizations must take into account human abilities and limitations to be effective tools for exploration and communication. In this feature review, we discuss key challenges and opportunities that arise when leveraging the sophisticated perceptual and conceptual processing of the human brain to help researchers understand brain structure, function, and behavior.

Exploiting the perceptual processes of brains to understand brains

The human brain is one of the most complex systems that scientists have ever tried to comprehend. Each of its 86 billion neurons has an average of approximately 5000 synapses, resulting in roughly 430 trillion synapses in the cerebral cortex alone, and perhaps 1000 times as many molecular-scale switches [1]. In the face of this complexity, how can scientists hope to circumvent the Catch-22 suggested by the adage 'If the human brain were so simple that we could understand it, then we would be so simple that we couldn't' [2]? We believe that progress in understanding the brain will crucially depend on developing data-mining techniques and visualizations that make structural, functional, and behavioral neural patterns intuitively graspable. Due to the complexity of the brain and the diversity and amount of data that scientists collect from it, understanding it will likely be an effort necessitating coordination among experts from different fields of sciences: social sciences, life sciences, physical sciences, mathematics, computer science, as well as engineering. Cognitive science, because of its interdisciplinary nature, is well positioned to supply useful methods and tools for understanding the human brain because it is an interdisciplinary home to scientists interested in the power and limitations of human visual processing, the determinants of effective visual depictions, and neuroscientists with detailed knowledge of neural patterns.

One of the most promising approaches for enabling us humans to understand our own brains is to develop visualization tools that take advantage of the millions of years of evolutionary research and development that have gone into construction of the human visual systems. By harnessing data mining and visualization tools, extremely large data sets that would otherwise be impenetrably complex can be converted into carefully crafted visual representations that can be effectively processed by the brain itself. Some of the most commonly used visualization choices for neuroscience data are detailed in Box 1.

Sophisticated understandings of brain structure, function, and behavior depend on re-representing quantitative and qualitative data, but seemingly neutral choices regarding data acquisition methodology, data analysis, and visualization can have a major influence on the final interpretation of the results. As an example, consider scientific understanding of how brain regions are interconnected, a core pursuit of neuroscience [3]. White-matter tracts are the principal anatomical structure responsible for transmitting signals from one cortical region to other distant regions. Unfortunately, a simple brain dissection will not reveal the separate white-matter tracts because they are hopelessly intermeshed by visual inspection. To appreciate the organization of white matter into tracts, modern, multistage data transformation processes can produce the visualizations shown in Figure 1. Figure 1A and B contrast the anatomy of the corticospinal tract and arcuate fasciculus, estimated with two different commonly

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Box 1. Guided visualization design and frameworks

Making sense of data by designing appropriate visualizations is a complex process that involves not only human perception and cognition [88,89], but also data mining, visualization algorithms, and user interfaces. Different conceptualizations of the overall process have been developed to understand and optimize this process, and to improve human decision-making capabilities. Among others, process models focus on key sense-making leverage points [90], the match between pre-conceptualizations and expectations of visualization designers and visualization readers [91], major data transformation and visual mappings [92], or describing visualization design and interpretation to support workflow optimization and tool design. Key visualization types are listed in Table I.

Table I. Key visualization types

Name	Description	Examples[a]
Tables	Ordered arrangements of rows and columns in a grid; grid cells may contain geometric, linguistic, or pictorial symbols	Figure 4A
Charts	Depict quantitative and qualitative data without using a well-defined reference system	Examples are pie charts in which the sequence of 'pie slices' and the overall size of a 'pie' are arbitrary, or word clouds
Graphs	Plot quantitative and/or qualitative data variables to a well-defined reference system, such as coordinates on a horizontal or vertical axis	Figures 2, 3A, 3C
Maps	Display data records visually according to their physical (spatial) relations and show how data are distributed spatially	Figures 1A–F, 3B, 4C–E, 5A–C, 6A–D
Network layouts	Use nodes to represent sets of data records, and links connecting nodes to represent relations between those records	Figure 4B; see also network overlays on brain maps in Figure 4C,D

[a]Figures cited refer to those in the main text.

used tractography methods. The estimated anatomy differs substantially. Furthermore, the tracts project to strikingly different cortical regions (Figure 1C,D; [4–6]). Research groups using a variety of related methods have come to different conclusions regarding the geometrical structure of the human white-matter tracts. For example, some researchers have claimed that tracts are organized in sheaths of white-matter crossings with strict geometrical structure [7], as shown in Figure 1E, whereas other researchers have criticized the evidence supporting such strict organization [8].

Figure 1 and the corresponding debate [7,8] show one shortcoming of human perception and cognition: existing preconceptions impact future actions, including the collection, analysis, and visualization of data on the human brain. If one were to view only one of the visualizations in isolation, one might well be convinced that the visualization simply reflects the 'true' structure of white-matter tracts: the cycle of subjective perception and cognition can result in a self-fulfilling prophecy. The beauty and concreteness of visualizations can encourage investigators to take them literally, at face value [9,10]. However, all visualizations are created using many highly parameterized data cleaning, merging, analysis, and visualization algorithms (Box 2), and the interest to see certain patterns and dynamics might well lead to attempts to extract and emphasize them in the final rendering, as the juxtaposition of the different visualizations in Figure 1 highlights. That is, proper selection of analyses and visualizations are key for the design of objective visualizations, as are expert interpretations of visualizations.

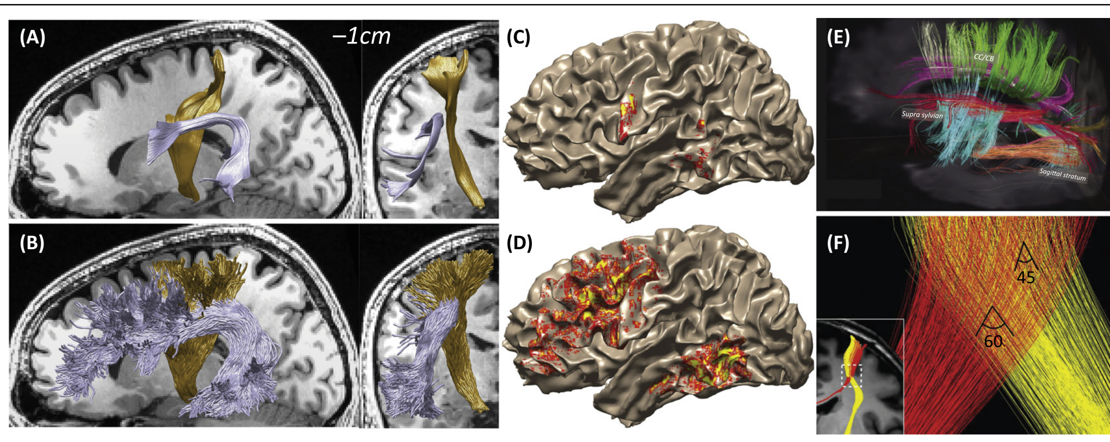

Figure 1. Anatomical visualization methods of human white matter. The panel on the left depicts trajectories of the human corticospinal tract (CST; gold) and arcuate fasciculus (AF; purple) identified using diffusion-weighted magnetic resonance imaging and deterministic **(A)** or probabilistic **(B)** tractography methods. The center panel depicts cortical projection zones of the AF estimated using deterministic **(C)** and probabilistic **(D)** tractography. The right-hand panel depicts white-matter fascicles apparently organized in sheaths with 90° crossings **(E)** [7] or crossing at different angles **(F)** [8]. Reproduced, with permission, from [4] (A–D), [7] (E), and [8] (F).