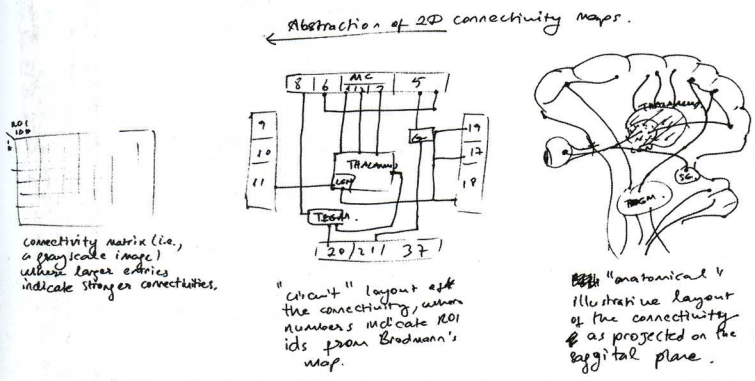## Exploring Brain Connectivity with Two-Dimensional Neural Maps
by Çağatay Demiralp

The goal of this project was to provide a representation and mode of interaction that would make it easier for neuroscientists to explore the intricate neural connectivity of the brain. The source of the brain connectivity information used was diffusion-weighted magnetic resonance imaging (DWI).

Figure 1 An example of a tractogram, where tracts are rendered as tubes.

A relatively new medical imaging protocol, DWI, now enables the estimation of neural pathways in the brain as a collection of space curves called a tractogram (see Figure 1). With some stretch of the terminology, each curve in a tractogram is also called a tract. Because DWI is the only widely available non-invasive method providing a window into the connectivity of a living brain, study of tractograms (i.e., tractography) has important applications in both clinical and basic neuroscience research on the brain. These datasets, however, have a visual complexity proportional to the intricacy of the axonal brain connectivity. And, with increasing DWI resolutions, this visual complexity is becoming greater and greater. It is thus often difficult for practitioners to see tract projections clearly or identify anatomical and functional structures easily in these dense 3D curve collections.

INTERACTIVE GRAPHICS

Abstraction of 2D connectivity maps.

connectivity matrix (i.e., a grayscale image) where larger entries indicate stronger connectivities.

"circuit" layout of the connectivity, where numbers indicate ROI ids from Brodmann's map.

"anatomical" / illustrative layout of the connectivity as projected on the sagittal plane.

Figure 2 A sketch from our notebook considering different levels of abstractions for 2D brain connectivity representations. Left: connectivity matrix. Middle: circuit layout. Right: anatomical illustration. The degree of abstraction decreases from right to left.

And so, we began thinking about new representations to improve understanding and the exploration of these datasets (Figure 2 shows a snapshot of a thought experiment about this challenge in our notebook). We envisioned that these new, and possibly simpler, representations would be typically used in tools where both the new representation and the conventional 3D tubular tractogram model would be displayed together and user interaction on their views would be linked.

Our first attempt was to use a 2D point-set representation of tractograms, where each tract was represented with a single point in the plane. Placement of the points in the plane reflected the configuration of the tracts in the tractogram that they represent. For example, when two tracts followed a similar path, then their corresponding point representations were placed in nearby points on the plane. Figure 3 shows a screenshot from a prototype tool using this representation.

Figure 3 A 3D tractogram model (left) and its 2D point-set representation (right). Interactions on both representations are linked. For example, whenever a primitive (tract or point) is selected in either representation, then the selection is reflected in both. The current selection is higlighted with red in both views. Tracts (and their corresponding point representations) are colored based on their similarity: similar tracts are assigned similar colors and dissimilar tracts are displayed with dissimilar colors.
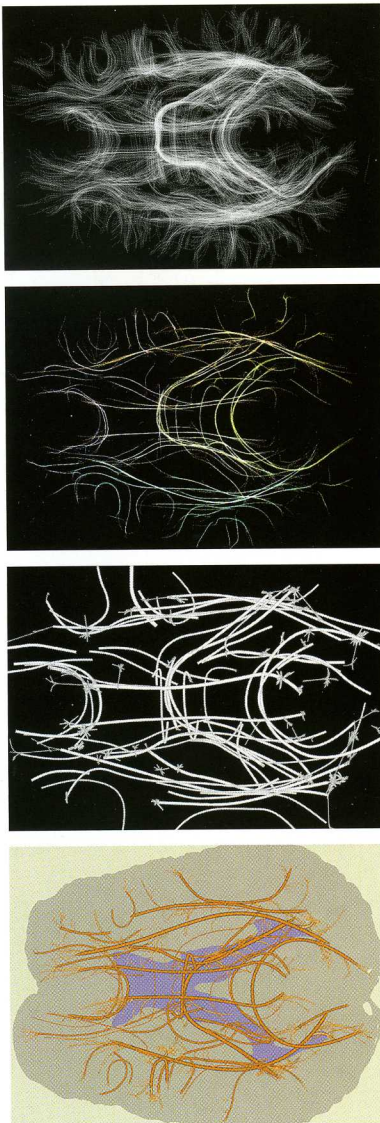
Figure 4 Iterations of the 2D neural path representation. In the final version (bottom), each stylized curve represents a bundle of tracts. Curve widths are modulated with the number of the tracts in the corresponding bundles. The blue region indicates the ventricles, a major anatomical landmark in the brain. The gray background is a horizontal silhouette of the brain surface. The final form of the representation was decided based on the degree to which it possessed the following characteristics: 1) simple but informative, consistent-multiscale axonal connectivity, 2) two-dimensional stylized look, and 3) useful anatomical context.

One common criticism we received from our neuroscientist collaborators, however, was that the 2D point-set representation did not have sufficient anatomical context by itself. In other words, it was too abstract for quick understanding.

Inspired partly by geographical maps and 2D illustrations seen in medical textbooks, our next approach was to represent neural tracts with 2D curves. This would also give the familiarity and anatomical context sought by the practitioners — remember neuroscientists are used to looking at cross-sectional images of the brain.

From the beginning we intended to take the notion of brain "mapping" literally by using the geographical map metaphor—producing a representation of the brain that can be viewed, interacted with, queried, and enriched just like an online geographical map. The highly popular online geographical map service Google Maps provided a practical way of implementing our idea on the web. We iterated several times while constructing the 2D path representation. Figure 4 shows a few intermediate results and the final representation.

Figure 5 shows screenshots from a standalone tool and a web application using the 2D neural path representation. Throughout this project, we had two common-sense strategies in mind to reduce visual complexity: abstraction and nested multiscale hierarchization. We believe that the resulting prototype was a successful implementation of these strategies. Our 2D path representation helps in fast multiscale exploration of axonal brain connectivity. Also, the web interface provides a familiar and efficient online interaction framework to share datasets, and, more importantly, it gives users the opportunity to integrate and enrich their data with the vast knowledge base of the web (see Figure 6).

INTERACTIVE GRAPHICS
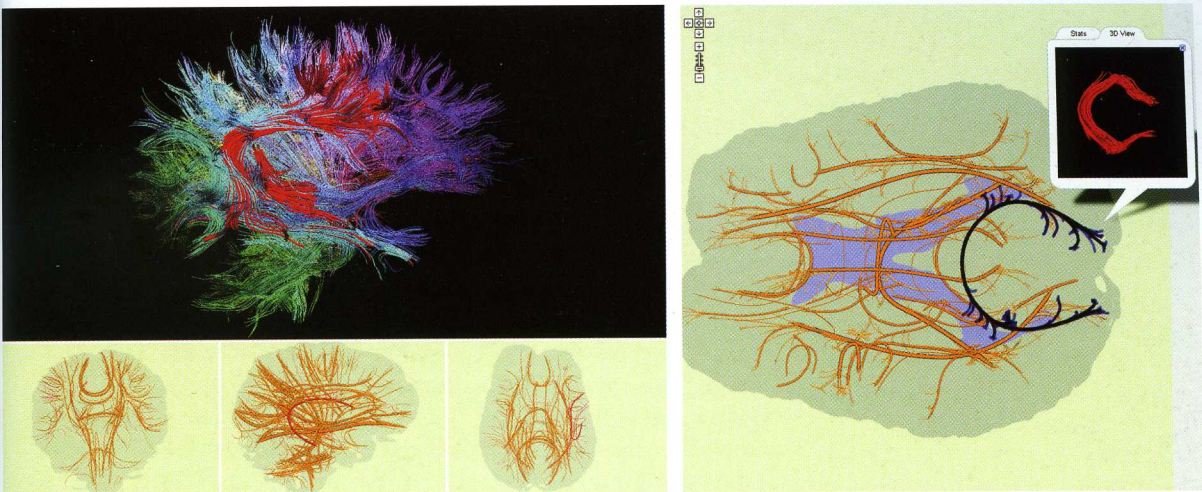
Figure 5 Schematic planar projections of DTI tractograms as part of a standalone interactive system (left) and as a web-accessible digital map (right). In the stand-alone application, interactions on the 3D and 2D views are linked. Shown in the pop-up window on the right is the "brain view" of the selected tract (analogous to "street view").
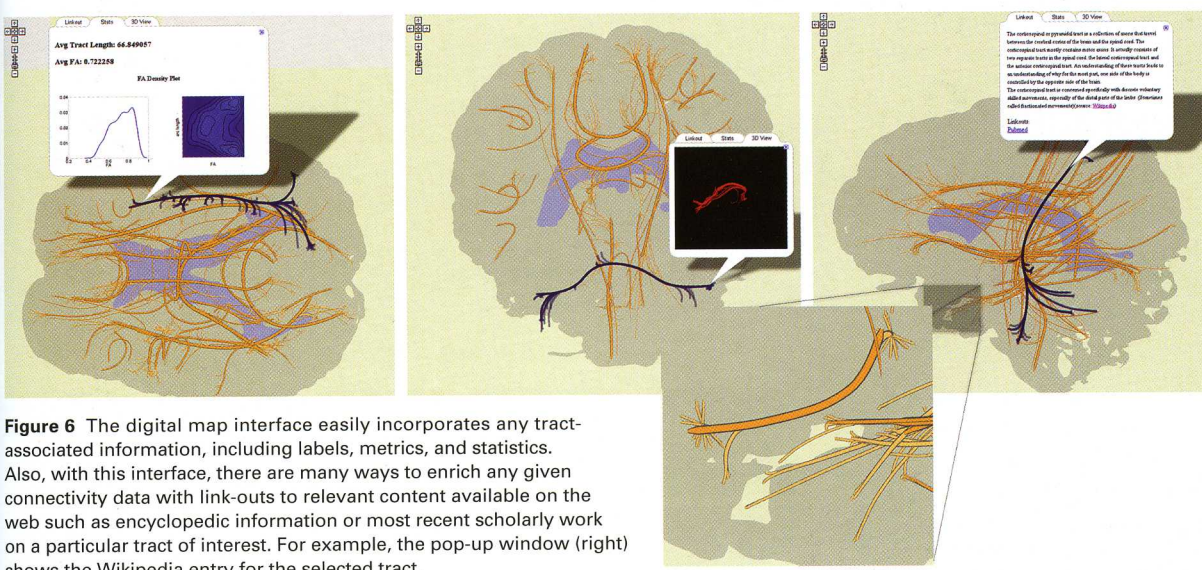
Figure 6 The digital map interface easily incorporates any tract-associated information, including labels, metrics, and statistics. Also, with this interface, there are many ways to enrich any given connectivity data with link-outs to relevant content available on the web such as encyclopedic information or most recent scholarly work on a particular tract of interest. For example, the pop-up window (right) shows the Wikipedia entry for the selected tract.