7 Networked Neuroscience: Brain Scans and Visual Knowing at the Intersection of Atlases and Databases

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1 Introduction: Seeing the Brain

Brain scans have been in heavy circulation these past two decades as some of the most fascinating and ubiquitous digital images in scientific and cultural spheres. Such images contribute to the constitution of the brain as an object of knowledge (De Rijcke 2008a, 2008b), and of the mind-in-the-brain (Beaulieu 2000). Part of their influence stems from how brain scans tie in to the biologization and digitalization of behavioral and psychological processes. The discrete, mapped-out bright bits seem to provide visual proof for the existence of material substrates of behavioral mechanisms, and for the claim that the basis of the mind is biological. The scans reify the brain as a locus of control and as a site of neurological, neuropharmacological, and neurosurgical intervention, or even of self-improvement (Brenninkmeijer 2010). Their importance should also be understood in relation to what has been hailed as "neurosociety" (Schleim 2010) or a "neuroturn" requiring scrutiny (Littlefield and Johnson 2012). However, these important critical reflections on the proliferation of neurodiscourses in the humanities and social sciences do not fully address the particular roles played by the visuality of brain scans. This visuality intensifies the focus on the neurosciences by other scholarly fields, as part of a sociotechnological turn toward visualization (Joyce 2006) and, in particular, in relation to possibilities for circulation, transformation, and manipulation of digital media. Brain scans purportedly make up ideal boundary objects between disciplines, and between specialists and a lay public (De Rijcke and Beaulieu 2007). They enable the multiplication of witnesses of neurological conditions and states of mind, while at the same time grounding such conditions in the empirical, the observable. As icons of neuroscientific progress in an extremely networked and visually oriented culture, they proclaim new developments for ever-wider audiences.

Given the wide and potentially weighty circulation of brain scans, how are we to understand them in relation to scientific and broader visual culture? In this chapter, we address this question by analyzing the development of authoritative collections of brain scans known as "brain atlases" since the beginning of the "Decade of the Brain" (the 1990s). We set out to investigate the conditions that make brain scans authoritative visual objects and analyze three important dimensions of scans. We show how scans are increasingly parts of *suites* of networked technologies, rather than standalone outputs. We then trace the increasing presence of databases of scans in the constitution of atlases, and outline the consequences of what we call *database logic* for visualizations of the brain. The third development we discuss is the role of scans as *interfaces* that serve to open up a range of possibilities, rather than to stand in as fixed representations. Together, these dimensions help characterize the visual in digital and networked settings of contemporary science, and they enable us to trace how the very concept of the authoritative image has been transformed.

Brain scans and atlases as visual evidence

The point has often been made that brain scans are not snapshots, and cannot and should not be understood in terms of a photographic register. Several analyses have shown that a number of assumptions of mechanical objectivity (Daston and Galison 2007) associated with photographic realism do not hold for brain scans. For example, the possibility of relying on the physical truth chain established by light particles touching an object and moving to a photographic plate has been challenged, in the context of digital imaging and data reconstruction needed for scanning (Beaulieu 2002a; De Rijcke and Beaulieu 2007). The realism associated with photographic representation has also has been critically scrutinized (De Rijcke 2010) as well as the faith in a standardized mechanical process that is free of intervention (Dumit 1994; Joyce 2008). Last of all, the overinvestment in the "observer's" ability to detect meaningful differences between scans has also been exposed when it comes to complex digital scans (Dumit 2004). In addition to deconstructing brain scans, these studies emphasize the complexity of brain scan images, the importance of context in constituting their meanings, and the work that goes into presenting them as autonomous proofs of intrinsic conditions in the brain and of the localization of particular functions.

While it is important to deconstruct the representational idioms associated with brain scans—and we have contributed to such work ourselves—we are also eager to develop critical work on brain scans that pays attention to the media and mediation (Bolter and Grusin 2000) and the spatialities (Lynch 1991; Hine 2006) of their production and use. Scans are both digital and networked images that depend on "suites of technologies" (Shove et al. 2007) for their constitution and meaning, rather than on single devices. These suites of technologies include digital images, data models, databases, screen-based interfaces, and electronic networks. The entwinement of these tools signals the limitations of a conception of scientific research that emphasizes fixed, authentic, mechanically obtained objective representations, to be consulted and evaluated by an observer.

The development and use of atlases is an important scientific activity that involves the networking of brain scans in and through databases and interactive interfaces. Atlases are authoritative kinds of images, and much is at stake in their creation. They make public the aspirations of the scientists who produce them, and reveal preferred epistemic and ontological stances of a scientific field (Daston and Galison 2007). Given the common understanding of digital images as mutable, and given that they do not partake in many of the assumptions of photorealism, an important issue concerns how these images can still be authoritative.

Furthermore, by focusing on the atlas, a form that embodies and shapes scientific authority, we are able not only to discuss the normative potential of brain scans, but also to link that discussion to the history of atlases and of objectivity. Not only are some images more or less objective, according to specific standards, but these standards also vary from discipline to discipline, between time periods, and according to context—whether they are used for scientific or for clinical purposes, for example. We therefore propose an approach that examines how the authoritative status of these images is actively constituted, rather than simply revealed through what they represent (also see De Rijcke 2010). We use the concept of "authoritativeness" to evoke an emergent, distributed and interactive mode of visual knowing.[1] We prefer that term to "objectivity," especially as articulated in the work of Daston and Galison, where objectivity is illustrated by visual forms and treated as an immanent aspect of images produced according to certain norm-laden practices.

In order to trace how authoritative brain images are produced through suites of technologies, database logic, and interactive interfaces, we draw on ethnographic fieldwork and archival research on atlases of the brain.[2] The empirical material we discuss concerns the International Consortium for Brain Mapping (ICBM), a North American-based research program that became internationally important through the dissemination of its standards, protocols, and reference works, including databases and atlases. The early years and policy context of this program are detailed elsewhere (Beaulieu 2001), but it is relevant to note that neuroscientific, clinical, and bioinformatics components were all represented within the consortium, with each component bringing its own visual culture to the project. In particular, both clinical-radiological traditions (Joyce 2006) and modeling and computer visualization approaches coexisted as frames of reference among the stakeholders of the program (Beaulieu 2002a).

By covering nearly two decades of work, we are able to analyze the incorporation of digital and networked images of the brain both in lab practices and in formal and informal scientific communications. In the late 1990s, the presence of the human observer was treated as somewhat residual, a glitch in the smooth pipeline that would soon be removed through the improvement of algorithms and processing abilities. The emphasis on automation in the development of new atlases was very much in line with more general moves to quantify and rationalize medicine (Berg 1997; also see Hine 2008 on computerization movements). Compared to previous brain-mapping practices, digital atlases introduced new elements of control and restraint in achieving what we then labeled "digital objectivity" (Beaulieu 2001). A decade or so later, user involvement had shifted. Far from being residual, it is healthily persistent. Interfaces to enable and support such human-observer involvement seem to be proliferating rather than disappearing. As technological developments have affected the way data is processed, integrated, and visualized, the role of the observer has not been left unchanged. At the same time, digital atlases continued to incorporate older conventions of imaging the brain: they "remediated" tradition (Bolter and Grusin 2000) as well as supported new practices. We now discuss these developments in more detail.

2 Scans in Suites

The notion of suites of technologies (Shove et al. 2007) has been fruitfully applied to design and interaction in general, and to radiological imaging in particular (Saunders 2009). It is also a powerful way to think about digital imaging and neuroinformatics, since it foregrounds the mutual dependence of images, screens, software, and interactions for creating and using new views of the brain. Observation and visualization around digital brain atlases increasingly take place behind a computer screen. This implies a shift in relations between observers, the brains they study, the technologies used for this purpose, and the institutional arrangements within which this happens (Beaulieu et al. 2012; Hand 2008). In the process, brain atlases are reconfigured as interfaces between different spatial realms: the brain as a newly constituted digital object, the material space occupied by embodied observers at the screen in a lab or hospital, and the expansive networked infrastructures through which the images circulate. Furthermore, the atlases function through interfaces that enable and demand interaction. By raising specific expectations and providing particular opportunities, these interfaces shape how the observer comes to know through images.

Starting in the mid-1990s, a number of US-based funding initiatives supported efforts to implement informatics approaches to neuroimaging. For researchers and funders involved in the ICBM, the prospect of accessing the human brain in vivo and mapping out various cognitive functions contributed to a renewed interest in producing atlases (Beaulieu 2001; De Rijcke 2010). The brain atlases that they built relied on a standardized space in which to measure brain function and structure (Beaulieu 2002b).

To compare this process to a more familiar geographical example, this move is similar to the development of a standardized projection of the earth and to the development of common coordinate systems. These ensure standardized georeferencing with GIS technologies, enabling them to work more or less seamlessly across platforms (and making possible the "switch" from "map" to "satellite" view on Google Maps).

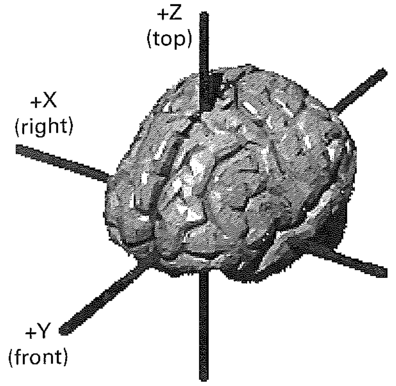

Figure 7.1
An illustration of the implementation of Talairach space. This space was described using Cartesian coordinates (along *x*, *y*, and *z* axes), which enabled researchers to transform and merge different kinds of information about brains, making different imaging modalities and different brains comparable. http://www.talairach.org/daemon.html.

The elaboration and adoption of a standardized "brain space" coevolved with the development of new digital brain atlases. Because of the possibilities for data integration and computation offered by a quantified, grid-oriented brain space, what came to count as a "reference" brain changed. Rather than using one well-described specimen as a reference, many atlases developed during this period were made up of "averaged brains." The researchers considered these to be better reference points, that is, to offer a better baseline from which to pursue investigations. As the constitution of atlases changed, so did the kinds of uses to which they were put:

> An atlas of the brain allows us to define its spatial characteristics. Where is a given structure, relative to what other features, what are its shape and characteristics and how do we refer to it? Where is this region of functional activation? How different is this brain compared with a normal database? An atlas allows us to answer these and related questions quantitatively. (Toga and Thompson 2000, 635)

The emphasis in these new atlases came to lie in the possibilities for manipulating, generating, and displaying information spatially. A spatial organization of information in digital atlases was the meeting point of two important developments. First, images—or more precisely, voxels—were coupled to coordinates in digital media. Second, scans that were described in terms of spatial coordinates could be linked to database and computational possibilities. The use of informatics to constitute and manipulate digital objects therefore changed the structure and content of atlases. The kinds of instruments that were needed to understand brain scans changed as these practices were adopted, since computational processes and workflows became important elements in the constitution of the brain and mind as objects of study. Similarly, new kinds of experts were recruited by neuroimaging labs in order to run experiments, since computer science expertise was increasingly needed to develop and manage databases and processing.

The atlas image is therefore not a normative scan to be compared visually to another scan. Instead, the atlas takes on features of both tool and representation, of epistemic and technical object (Rheinberger 1997), since it is both a tool that can be used to interrogate new instances and an object that improves by including new instances. The difference is not simply one between print on paper and pixel on screen. The scan to be interpreted is constituted through processing in relation to the "average brain" of the atlas, so that only certain kinds of differences will become apparent. Whereas a cascade of representations gained authoritativeness because of the growing distillation and augmentation of data in each subsequent step (Latour 1990), the ICBM atlas is authoritative because it enables further manipulations and evaluations.

Setting up "pipelines" to produce images

In the development of digital atlases, a standard space made it possible to manipulate different scans produced through different techniques (for example, different scanners) and from different subjects. By transforming them to a common "space" via a series of operations, they could become comparable and could be integrated into a single visualization. While there is some variation in the emphasis and techniques used, two challenges are especially prominent for those developing these new atlases. First, the right set of transformations must be identified and implemented through computational processes. For example, differences due to different scanners or even to different scanning sessions must be removed, since they are considered irrelevant to understanding the brain. Since brains vary in their anatomy, size, or even orientation in the scanner, all these elements, which are supposedly irrelevant, can be removed without loss of relevant information about the brain. Furthermore, the differences that *do* matter must be maintained. This means that the relative size or position of different parts of the brains must be preserved through and in spite of other transformations. Second, in the constitution of most atlases, other features of subjects assumed to be relevant to the brain's anatomy or organization are also recorded and taken into account. A whole list of characteristics, such as handedness, history of mental or neurological health, bilingualism, sex, and so on, come to function as metadata in the database that underlies these atlases. In more recent atlases, DNA samples are also collected for future correlation between scans, data about subjects, and genetic information. While no researcher or user of these atlases would claim that the characteristics are definitive and contain all explanatory information, this systematic correlation does enact the modernist ideal of the individual as the sum of its characteristics (Beaulieu 2000).

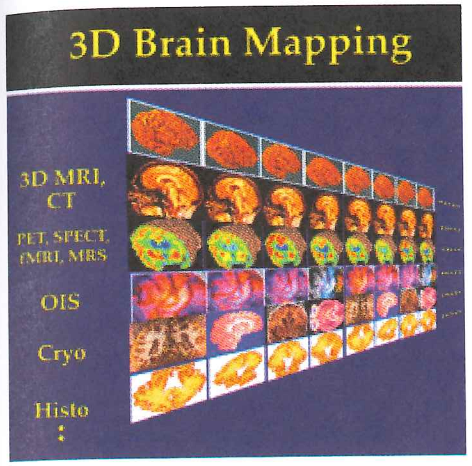

Figure 7.2
Each row represents data from one modality (kind of scanner or procedure). Each column represents data from one subject. Note the well-ordered presentation of data, which symbolizes the "pipelines," and the possibility for endless extension (open-endedness) of modalities and of subjects. http://www.loni.ucla.edu/~thompson/NEW/brain_mapping.gif.

This approach was developed in relation to "normal" brains, but also to variations considered relevant for understanding disease and cognition—for example, there is an atlas of the "Alzheimer's brain" (Thompson et al. 2003) and of children's brain development (Almli et al. 2007).

The set-up of pipelines as sets of standardized tasks and explicit operations to be performed by computers guarantees that the emerging object, made up of multiple kinds of data, will reveal the brain. These pipelines feed the atlas, providing the "raw" data that will constitute authoritative images. The pipeline ensures that the scans are purified of unnecessary information, that all metadata considered relevant are included, and that all voxels are made equivalent. Like the trust based on the mechanical objectivity of photography, the pipeline exudes standard handling and processing and constraining of subjective intervention. In some ways, these computational technologies push the values of control and restraint to new heights in the constitution of authoritative images. Yet these pipelines are also built with specific "manholes" that enable the user to remain involved in the process. In fact, they even demand that the user remain involved, in order to ensure the quality of the processing in the pipeline. Particularly interesting is the way a human observer can detect "garbage" in a way that a computer can't. Some of the visual inspections required in pipelines aim to identify when scans of phantoms (dummy objects used to calibrate scanners) rather than of human brains have wrongly been uploaded to data pipelines. (This is the neuroimaging equivalent of chucking out the photos taken with a thumb on the lens—a kind of image that a computer will happily process.) The latest developments in the production of these atlases offer an increase in the modularity and portability of pipelines, allowing users to tailor the pipeline to their own needs using "processing building blocks" (Van Horn and Toga 2009) and to interact with the infrastructure that runs the pipelines (such as the Grid) via graphical user interfaces. We return to the importance of interfaces later in this chapter. For now, we want to stress that, through the development of informatics, brain scans have become embedded in and reliant on a digital and networked context. The scan not only relies on processing via scanning and software technologies in order to then be compared to an atlas of the brain, but it can only be meaningfully generated and viewed in relation to the atlas and as part of a suite of technologies.

3 Deploying Database Logic and Probabilistic Thinking to Make Images

A second important development is the growing importance of database logic, which comes to the forefront of authoritative images. This development is related to digital media and the networked configuration of technologies, but it is distinct in the sense that it represents a particular investment in the organization and structure of knowledge produced through these images. Recall that when the scans processed through pipelines are aggregated to constitute a particular version of the brain, such aggregation can only be accomplished if the brain is represented as a set of voxels in a standard space, with voxels having *n* attributes (kind of tissue, site of activation, etc.). As noted above, each voxel in the resulting image is calculated based on the corresponding voxel values across the database of scans. This leads to a "naturalization" of the voxel as a component of the brain, turning neuroimages into thoroughly digital and informational objects.

The atlas relies on database logic for the constitution of authoritative images. This means that, rather than relying on "capturing" a good image, researchers invest in gathering and labeling data and relating them. Furthermore, the searchability of the metadata in the database contributes to the adaptability of the atlas. Ideally, for neuroscientists, atlases would be created based on a particular feature—for example, age—for which large archives of shared neuroimaging data are tagged (Van Horn and Toga 2009). Because the atlas is mutable, it can be shaped to best suit the analysis of a particular scan. The possibility of selecting the right subset of scans in order to adapt the norm makes the atlas more authoritative, because more relevant to a specific case.

Besides producing average atlases, another way researchers use the database is to develop probabilistic atlases. In these images, the voxels do not represent absolute values such as averages, but rather probabilistic outcomes of calculations across scans in the database. Such atlases will indicate, for example, that the probability of a particular coordinate being located in area X of the brain is 89%. It is also possible to draw on the "features" that have been recorded in relation to the scans. By articulating a set of variables, a query can be formulated that leads to the constitution of a specific atlas: for example, of the brain of a left-handed female in her thirties. However, such tailoring of the atlas can only be done by means of parameters that are already codified as differences that make a difference (Beaulieu 2001). In that sense, atlases function just like classification systems that enhance and obscure particular aspects of knowledge. The atlases also further shape other atlases, as they serve as baselines for identifying other features that may be relevant. The generation of further knowledge, whether through large-scale comparison or analysis, is always done according to the parameters for which data have been coded. Potentially, each new scan added to the database improves the atlas, giving the database a "generative" dynamic (Waterton 2010).[3]

This constitution and use of the atlas foregrounds the database. In contrast to the averaged brain, the image in the probabilistic atlas is not derived or distilled and then removed from the scans contained in the database. Probabilistic atlases highlight the range contained in the database. They depart radically from traditional atlases because of the way they foreground objects as both variable and relational, rather than as discrete "specimens" or autonomous instances that can be understood on their own (for example, Gong et al. 2009). While the figures thrown up by a probabilistic atlas are clearly visually codified, with colors referring to precise quantitative values, the observer is invited to consider them not as absolutes but within a register of

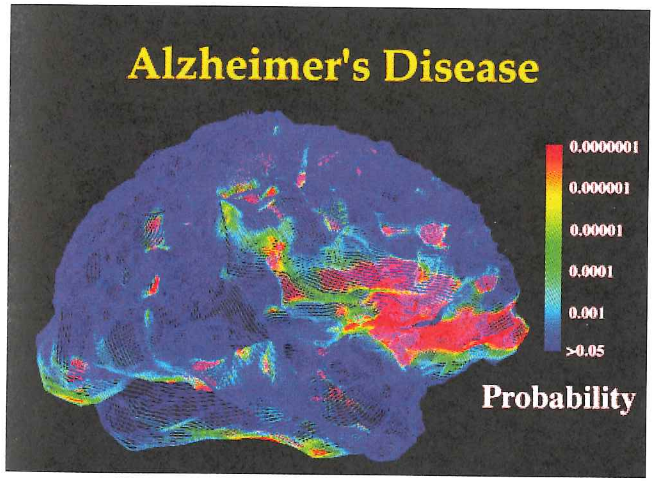

Figure 7.3
A probabilistic atlas from Thompson et al., *Journal of Computer Assisted Tomography* 21(4) (1997): 567–581. The recognizable shape of the brain is made up of colors that relate to a probabilistic key. It invites the viewer to consider the image as the outcome of calculations across a database, and in terms of a possible outcome—in this case, variation indicative of Alzheimer's disease.

possibilities. Accordingly, the register of possibilities is what lends authority to these atlases. By focusing on this aspect of images, we are drawn to consider the changing role of scans in relation to empirical, communicative, or analytic work in science. Furthermore, given the intensified relationship between image and database to which we draw attention, it seems urgent to consider how different kinds of databases will give rise to different kinds of visualizations.

4 The Atlas as Interface

The atlases constituted through databases embrace the range of possibilities contained in images of, and metadata relating to, the brain. These possibilities are not simply immanent. The interface, where these possibilities are presented *and* can be acted upon, becomes a crucial new aspect of visual knowledge production. It makes it possible to weigh different variables, or to alter the processing to explore how this affects the probabilities. This is more than a technical issue; interfaces link together investments in empirical investigations, mathematical and cognitive modeling, and the skills of the observer.

The increasingly networked settings in which brain atlases take shape facilitate the intensification of collaboration between different neuroimaging laboratories, but they also deepen compatibility issues on the level of the databases to be pooled, the image modalities to be merged, the scanning protocols to be followed, and the tools used to process and analyze the data. Although standardization and automation are still offered as complexity reduction strategies, at the same time the atlases are increasingly equipped with integrative, comparative, and interactive features. These atlases are therefore also interfaces, where an observer is to consider, judge, and interact with the image as database.

To demonstrate this, we turn to the analysis of the production of a networked probabilistic atlas of human white matter (the whitish connecting nerve tissue underneath the gray surface of the cortex) by the ICBM. In 1999, one of the ICBM's partner institutes at Johns Hopkins University developed a method for translating magnetic resonance imaging (MRI) data into three-dimensional reconstructions of neuronal tracts (Mori et al. 1999). The method, which became known as diffusion tensor imaging (DTI), was said to open up a whole new territory for digital, "in vivo" scrutiny. A couple of years later, its most highly developed application was that of fiber tracking in the brain (Le Bihan and van Zijl 2002). A new kind of epistemic object rapidly emerged on the basis of DTI, generated in the context of large-scale projects that gather and process data across centers, scanners, and subjects.

The appropriation of DTI as a new "window" on white matter anatomy and brain connectivity was largely instigated by the circulation of the first *MRI Atlas of Human White Matter* in 2005 (Mori et al. 2005). It consisted of high-resolution two- and three-dimensional visualizations of the major white matter tracts. Interestingly, the atlas was made available both electronically and in print. Using an electronic format was very much in concordance with ICBM's neuroinformatics goals. The networked context increasingly reconfigures the atlas to different spatial realms, ranging from the local "brain spaces" on the screens of observers to the larger, federated databases of which the brain data was meant to be(come) part. This made these and other digital atlases essentially emergent or—in the words of the ICBM—"evolving."[4] The fact that Mori and colleagues also saw fit to publish a printed edition of the atlas points to the contemporaneous clinical and laboratory practices in which the digital images were being integrated. The continued relevance of printed atlases as "stable" reference points in increasingly networked settings is an example of the ways in which these atlases "remediate" tradition even as they support new practices (cf. Bolter and Grusin 2000).[5] This remediation is visible not only in the publication strategy, but also in the digital atlas images themselves.

Atlases both reflect and shape a discipline's research objects. They also delimit what constitutes "proper" observation and visualization for practitioners, and new representational conventions can bring about a situation in which "everyone in the field addressed by the atlas must begin to learn to 'see' anew" (Daston and Galison 2007, 22). The forms and presentation of the white matter atlas show that new visual forms require a reconfiguration of the observer (cf. Crary 1991). This atlas was mainly aimed at a readership of radiologists and surgeons who regularly dealt with connectivity impairment. At the time, most of them were new to DTI. The atlas makers therefore carefully set the stage for DTI by means of short verbal descriptions and comprehensible visual juxtapositions. Among other things, they argued that the technique was capable of doing something "conventional MRI" could not do: provide good contrast at the level of individual voxels, so that variations in white matter structure are properly displayed: "From an MRI point of view, the white matter generally appears as if it were a fluid-like homogeneous structure, which, of course, is not the case" (Mori et al. 2005, 1). Borrowing a phrase from media theorists Bolter and Grusin, it is as though the authors justify the use of DTI "because it fulfills the unkept promise of an older medium" (Bolter and Grusin 2000, 60). To fully advertise the impact of the new modality, the authors presented a visual comparison (see figure 7.4). This triptych defines the parameters for understanding the two- and three-dimensional images in the rest of the atlas.

From left to right, we see a T1-weighted magnetic resonance image (which represents differences in "T1 relaxation time," i.e., the time it takes various tissues to return to an equilibrium after magnetization), followed by a representation of variations in the direction of the diffusion of water molecules, and a color-coded version of the same information. (Note how the colors correspond to arrows in the top right corner.) The oval shapes drawn above the middle and right image are connected to a specific area in

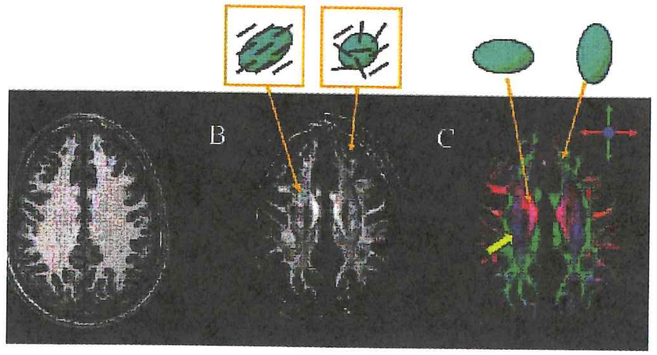

Figure 7.4

T1-weighted MRI, and two representations of anisotropy levels in the same slice. Water molecules preferentially diffuse anisotropically—toward and away from the cell body, parallel to the axons' length. The orientation of the restricted diffusion is therefore a factor in tissue characterization, next to its magnitude and shape (Le Bihan et al. 1991). The color-coded image on the right displays the direction of the measured anisotropy. For each of the slices (moving from left to right), a different level of detail, graphical explanation, and color are provided, emphasizing the increasing complexity and revelatory power of imaging modalities.

the brain through yellow arrows. They are meant to facilitate the visual appreciation of brain areas in which the diffusion is either anisotropic (unidirectional, elongated oval, brighter) or isotropic (random diffusion, round, darker).

The image on the left, which the authors designate as "conventional MRI," is the only one that does not have explanatory features. A large portion of the field of view is occupied by a flat, rather homogeneous mass. This "fluid-like structure" represents a segment of the brain's white matter. The authors deliberately chose an axial (horizontal) brain slice at a level where white matter dominates gray matter in terms of percentage. At no other slice level is this so obviously the case. The image is meant to provide a strong contrast with the diffusion-weighted anisotropy image in the middle, and to show how this "unique new MRI modality" provides a very different view on white matter structure, providing much more information about it.

The juxtaposition has yet more complex effects. Interestingly, all three images represent a constructed or simulated "digital space" (Lynch 1991, 63), since they are visualizations produced with a rendering algorithm. Despite major differences in data processing, the first and the second image are visually similar because both are represented in black and white, in contrast to the third image which is color-coded. What we see here is a *mise-en-scène* of a break between two imaging traditions. The black-and-white images evoke the immediacy and mechanical objectivity of photographic realism, while the color-coded image explicitly draws attention to its digital mediation.

The left and middle images remediate a long-standing radiological tradition, in which X-ray and computed-tomography scanning technologies have created familiar cultural objects (Joyce 2008). The "conventional MRI" is rooted in the opticist pictorial tradition that makes reference to "mechanical reproduction" (Lynch 1991, 72) and to "the position of the observer in a 'real,' optically perceived world" (Crary 1991, 1–2). These connotations are transferred to the diffusion-weighted image in the middle.

In the image on the right, the use of colors breaks with this tradition of invoking an "optical" truth. The colors are meant to be read as codifications of the direction of the largest principal vector in each particular voxel. The color-coded image is what Bolter and Grusin (2000) refer to as "hypermediated": it makes the viewer aware of the medium and the acts of representation that created it. This framing of DTI as part of a new epistemology is achieved through constant reference to "conventional" MRI, as a benchmark of anatomical "reality." The white matter atlas therefore emphasizes its digitality: its images are an outcome of novel forms of processing and of powerful calculation. The atlas's appeal is based on the standardization and pipeline calculations discussed above, but here we see how the observer needs to be taught to see anew, to appreciate that the visual features of the atlas rest on a new approach to visualization. This signals both the scale of changes in atlases and the enduring importance of the observer, who remains indispensable.

In the studio[6]

One of the purposes of the publication of the *MRI Atlas of Human White Matter* was to persuade researchers and radiologists to integrate DTI with their own practices and laboratories. As such, the atlas also played a role in coordinating professional activities and investments, becoming part of the pool of narratives that frame how images are to be interpreted (Cohn 2007; Roepstorff 2007; Saunders 2009). As we have seen, scans in digital atlases can act as intersections between existing pictorial traditions and new image parameters, depending on the visual form given to the image data.

Diffusion tensor imaging is not a straightforward task: image production with it requires "involved post-processing" behind a desk, after the "raw" data have been gathered by the scanner (Jiang et al. 2006, 106). This is one of the ways in which the configuration of the network in which DTI operates differs fundamentally from "conventional" MRI, which also requires processing but in which end users have less influence on image production. To make DTI available as a new tool for use with ICBM-networked brain databases, technological changes were required in the pipeline set-up, in the trajectory from image data acquisition by a scanner to the visualization of white matter tracts on a computer screen, and in the data exchange between the local image database and the ICBM-federated "reference system." Several software packages were specifically designed for these purposes. One of these packages, called DtiStudio, which had been used to produce the white matter atlas, became the ICBM standard processing program for tensor calculation, color mapping, fiber tracking, and 3D visualization.

DtiStudio prescribes how the "raw" diffusion-weighted image data should be handled and organized for further scrutiny. The software manual takes the reader through all the steps implicated in the "involved post-processing" procedure, but not before emphasizing that its "user-friendly interfaces" make DtiStudio the requisite image-processing tool for practitioners and researchers interested in brain connectivity (and disorders of it). A "user-friendly interface" in this case means a Microsoft Windows interface. The program mimics other Microsoft applications, and claims to combine smoothly with them. The manual addresses its intended audience in a straightforward manner, exuding fun and effortlessness. The authors stress that the software takes up only a few hundred kilobytes to install, and that after installation users are immediately "ready to play with the program." Provided that there is enough memory for the (much larger) datasets, the software can be used on virtually any computer, at home or in the laboratory. In addition, "most operations can be done with only a few clicks" (Jiang et al. 2006, 1). Users can cut and paste images from DtiStudio to the Word file of an article in progress, upload images to their web pages, or email interesting findings to colleagues after data processing. These and other elements of the software imply an interactive, dynamic process of image production and circulation.

One of the software's salient characteristics is that visual and manual processing is neither marginalized nor fully standardized: the interface provides possibilities for interacting with the data through the image, but does not dictate what should be done (cf. Coopmans, this volume). Users are invited to engage with the images displayed on their computer screen by adding or extracting colors, defining regions of interest, or subjecting parts to several algorithmic filters. The shift from a situation in which mediation was erased as much as possible (Bolter and Grusin 2000) to one of "hypermediacy" deeply affects both image production and the status of the images themselves. In DtiStudio, "real" or "objective" images are not static visualizations of brains, but flexible tools (cf. Rheinberger 1997) that enable further processing. The images are amalgamations of standardized calculations and physical interventions (such as mouse movements). Although the process is partly standardized, users maintain an interactive relationship with the images on the screen. Researchers or clinicians who use the software can generate and isolate various white matter tracts, have them appear and disappear on the screen, change their color, or play with the three-dimensional renditions of white matter structure. They can choose certain modifications on the basis of their experience with brain anatomy, or create visualizations of white matter that have never been created before. By presenting an indeterminate range of imaging modalities and options for further processing, the software allows users to tailor their experience to the purpose of their research or clinical study.

The scans are thus placed in a complex infrastructure that enables visual knowing in a manner distinctly different from the consultation and evaluation of fixed, mechanically obtained objective representations by an observer. However, despite the emphasis on hypermediated, interactive visualization, the "immediacy" of mechanical objectivity continues to have some influence on conventions for proper observation and visualization. We showed how the apparent transparency of "conventional" MRI served to position DTI in the existing visualization traditions and knowledge structures of radiology. In addition, DTI makes use of familiar anatomical conventions for displaying and analyzing preserved slices of the brain and for composing anatomical atlases. What is more, by using the "conventional" MRI as a reference, the pictorial and observational conventions of clinical radiology act as an important filter to the digitally constituted and hypermediated images. Furthermore, these conventions are inscribed in the new DTI database logic by software packages such as DtiStudio, by enabling the weighting of different features and the selection of subsets for visual inspection, among other things. The authoritativeness of brain scans and atlases is increasingly produced through such database logic as well as through the interactive interfaces and suites of technologies in which brain imaging data are embedded and which shape their use.

5 Conclusion

By examining present-day brain imaging atlases, we were able to focus on changes in existing configurations of users, visualization technologies, and atlas images, and to relate these to the transformation of the concept of the authoritative image. The atlases we analyzed are increasingly taking shape at the intersection of digital, networked, and computational technologies. As we have seen, huge investments are made in the development of standards and protocols to make scans aggregable and comparable. These are then leveraged to impart authority to the atlases. The authoritative status of these new atlases can be achieved through averaging, or through probabilistic approaches that link an "end" or "target" image with the underlying data. The integrity of this underlying data is in turn warranted by the implementation of the "pipeline" that organizes and purifies these scans, and by sophisticated transformation algorithms. At the same time, a number of interfaces are specifically built into this process, interfaces where an encounter takes place with a human observer who orients to these scans as visual evidence. Consequently, these atlases draw on both the radiological tradition and the computational, data-driven approach. While these various epistemic regimes coexist, and can even depend on each other, the kinds of brains produced are changing along with the kinds of instruments, kinds of work, and kinds of experts needed.

An important characteristic of these brain atlases is that they act as bridges between images in databases, types of data, technological platforms, image modalities, scales, and dimensions. They remain in continuous dialogue with the databases that underpin them. Adjustment always remains a possibility, and can be spurred by temporal, computational, or visual considerations, depending on the practices of clinicians and researchers. The images themselves also act as interfaces (cf. De Rijcke and Beaulieu 2011). They do not only reveal epistemic objects; they also constitute relations and opportunities—ranging from local interfaced practices of handling the data to aggregate-level large-scale federated databases. The interactive dynamics between local and federated databases increasingly complicate clear-cut distinctions between these levels. Together with the scanning technologies, software, screens, databases, and the role of the observer in relation to them, the images partake of the dynamic of "generative exploration" that Waterton (2010, 654) identifies with archives. Yet the flexibility and creativity this suggests are not boundless. Atlases become entwined with networked infrastructures and become increasingly obdurate as their implementation spreads.

To reveal the epistemic and ontological assumptions around images of the brain, it is important to recognize their embeddedness in suites of technologies (Shove et al. 2007), as well as the remediation (Bolter and Grusin 2000) at work in rendering them meaningful. The iterative and relational aspects of neuroimaging are central to the specific kind of authoritativeness that comes into play when these images are used in making claims about the brain, the mind, and the self. With brain scans in pipelines, the brain becomes a spatially configured set of voxels, whose tissue and other features can be computed, highlighted, compared, filtered, labeled, and drawn upon interactively. It becomes possible to switch between kinds of data, to go back and forth, to retrieve a brain as specimen in the average, to bring out the specific object in relation to a "population," and even to shape what counts as the "population."[7] Given the growing scope of the terrain of the brain, it is crucial to understand these dynamics in the creation of these images. Not only do they purport to show the structural characteristics of the brain, but they also claim to convey function, cognition, and sociality. Genetics are also increasingly coupled to neurobehavioral assessments and become metadata to the voxels in the space inside the skull, so that regarding the brain in these atlases is an increasingly layered exercise. It requires a specific sensibility to the particularities of networked databases of the brain—their size, the quality of images, the way in which digitization was implemented, and the practices of looking enacted through them—to see how these factors shape the constitution of the brain itself. The analytical tools we have put forth in this chapter contribute to developing such a sensibility. They clarify the role of the visual and provide an additional angle of critical examination of the neuroscientific turn, besides those of biologization of the self or bio-governmentality.

The approach we present also shows how to understand the entwinement of digitization, pipelines, database logics, and interfaces. We have traced how they come together to support an emerging kind of looking[8] and a new way to create images that matter. Interfaces such as the DTI and other probabilistic atlases demand "relational looking," through which the image is seen as a dataset in relation to the parameters of the atlas/database. In these atlases, observer involvement is distributed and iterative.

The database logic and the networked context of these atlases also add to a tendency toward iteration, malleability, and aggregation.[9] Crucially, these features are the result of important differences between images constituted through cascades of inscriptions (Latour 1990) and those produced through the alignment of computation and digital infrastructure and the development of images as interfaces. The possibilities of digital media contrast with the tendency to build unidirectional cascades in the use of print-on-paper inscriptions, which can be cascaded but not so easily reconstituted, nor re-formed along changing parameters.[10]

We should note that the role of interfaces and suites of technologies in producing authoritative images is not confined to brain imaging but can also be found in other forms of visual knowing (around databases of images) that could be labeled "mundane," such as getting to know a museum's collection (De Rijcke and Beaulieu 2011). Similarly, an emphasis on the fluidity and openness to further scrutiny of digital images can be found in everyday snapshot photography (Rubinstein and Sluis 2008). Such links between scientific and cinematic practices, between professional and amateur spheres, between science and art (Cartwright 1995; Kember 1991; van Dijck 2005), are important because they situate scientific images within culture.

As images become interfaces to networked databases, the dynamics of knowledge production change. Several of the dynamics we identify in this chapter reach beyond the neurosciences, and beyond scientific visualization at large: investments in standardization, in metadata and curation, and in the personalization of data, norms, and even infrastructures can also be found in other networked contexts for digital knowledge. The way images become connected leads to interactions that exceed the limits of single databases, kinds of data, technological platforms, image modalities, scales, and dimensions. These transformations are not simply a question of databases providing information more effectively through digital media. Rather, we are witnessing changes in the interaction with visual information, in the evaluation of what constitutes information, and in the production of visual knowledge.

Acknowledgments

The work presented in this chapter spans many years, and benefited from the insights, critique, and support of participants in our fieldwork, of our colleagues at Science and Technology Dynamics, University of Amsterdam, and at History and Theory of Psychology, University of Groningen, and of the editors. The writing of this chapter was informed by our work in the project Network Realism, for which the Virtual Knowledge Studio for the Humanities and Social Sciences provided financial support and

intellectual stimulation. Interactions with Paul Wouters, Susan Legêne, Annamaria Carusi, Sissel Hoel, Hannah Landecker, Lisa Cartwright, and Morana Alač in the course of this project were precious and much appreciated.

Notes

1. This mode of visual knowing is called network realism (http://networkrealism.wordpress.com/). The focus in this chapter is on one particular aspect of this mode of knowing, which is the production of authoritative images.

2. The fieldwork and archival research were conducted by Beaulieu and de Rijcke, respectively, for their PhD research in the late 1990s and late 2000s.

3. However, in order to enable clinicians to make diagnostic evaluations, or researchers to publish, the database is "frozen" in time to provide stability for a given period, and the atlas image recalculated only periodically rather than on an ongoing basis. The mutability of these atlases is therefore limited in practice.

4. http://www.loni.ucla.edu/ICBM/About/, accessed 28 January 2011.

5. Remediation is the dynamic by which digital (or other media) define themselves by borrowing from and refashioning other media forms such as radiology, photography, cinema, animation, television, etc. Remediation is not a one-way process, and we have already seen many examples of printed media remaking themselves in the image of websites or social media.

6. This section is named after a software program we discuss below, called DtiStudio. We aim to bring out the artistic connotation of the word "studio," which typically refers to a place to try things out and where room is provided for creative acts.

7. Recall the possibilities of having an average left-handed, 35-year-old female brain to use as baseline; personalization as a media option can also be found in scientific digital environments.

8. The framing of the observer's tasks also shapes visual practices: for example, in the case of the CT suites discussed by Saunders (2009) he observed "sacral looking," a search for revelation that will enable resolution of the intrigue posed in clinical diagnostics. In the cases we have analyzed, looking is configured either as detection of garbage, of blatant (for a human) noise in a given visualization, or as "a dynamic interaction between trying to find or to generate an image" (Cohn 2007, 99). In the former cases, the observer serves to bound or correct the exaggerations and overinclusive processing of the digital suites.

9. One of the most recent areas of development in these atlases is the aggregation and use of metadata as a way of further disciplining atlas data, or to link the data to what emerges as really important in the course of research, knowing that it cannot be articulated ahead of time. Tagging and using metadata to document provenance are common strategies, not only in digital brain atlases (Van Horn and Toga 2009) but also in data-sharing platforms across life and social sciences (Dormans and Kok 2010) and in social and cultural production (Beaulieu et al. 2012). These processes call attention to the increased importance of understanding how collections are curated. They also point to the need for the management of databases across disciplines, institutions, and countries—to understand not only atlases but also broader (scientific) digital visual culture.

10. Of course we should not forget that responsibilities come with these possibilities, since observers/users are expected to make appropriate decisions regarding adjusting, selecting, rejecting, or evaluating them. This responsibility highlights the need to understand the skills required to deal with these images (De Rijcke and Beaulieu 2011). It also calls for further studies that trace how observers and users are assigned particular responsibility in the very course of gaining expertise (Goodwin 1994; Alač 2008) and how agency and digital techniques intertwine.

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8 Rendering

Natasha Myers

1 Introduction

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