The space inside the skull: digital representations, brain mapping and cognitive neuroscience in the decade of the brain

Beaulieu, J.A.

Citation for published version (APA):
Beaulieu, J. A. (2000). The space inside the skull: digital representations, brain mapping and cognitive neuroscience in the decade of the brain

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).

Disclaimer/Complaints regulations
If you believe that digital publication of certain material infringes any of your rights or (privacy) interests, please let the Library know, stating your reasons. In case of a legitimate complaint, the Library will make the material inaccessible and/or remove it from the website. Please Ask the Library: http://uba.uva.nl/en/contact, or a letter to: Library of the University of Amsterdam, Secretariat, Singel 425, 1012 WP Amsterdam, The Netherlands. You will be contacted as soon as possible.
The Space inside the Skull

Digital Representations, Brain Mapping and Cognitive Neuroscience in the Decade of the Brain

Anne Beaulieu
The Space inside the Skull:
Digital Representations, Brain Mapping and Cognitive Neuroscience
in the Decade of the Brain

ACADEMISCH PROEFSCHRIFT

Julianne Anne Beaulieu
geboren te Moncton, Canada
Promotor: prof.dr. Stuart S. Blume

Faculteit der Maatschappij- en Gedragswetenschappen
Table of Contents

List of Figures.................................................................................................................. v
Note on Images and Figures Used................................................................................... vi
Acknowledgements ......................................................................................................... vii

Chapter 1 New Views of the Mind-in-the-Brain ............................................................... 1
  Brain Mapping and Representations ............................................................................. 1
  Representations in Brain Mapping: Physical Minds and Virtual Brains ................. 10
  Self, Embodiment and Biologisation .......................................................................... 10
  Digitalisation ................................................................................................................ 14
  Dimensions of Representations ................................................................................... 23
  An introduction for cognitive and neuro-scientists ..................................................... 25

Chapter 2 Building A Window on the Brain ................................................................. 26
  Anatomy: The mother of all neuro-disciplines ......................................................... 29
  Metabolic Landscapes ................................................................................................. 32
  Landmarks: Physical Concordance as Principle ....................................................... 36
    Plates of the Atlas ..................................................................................................... 37
    Head Holders ........................................................................................................... 38
    Templates .................................................................................................................. 39
  Standard Anatomy: From Matching to Translation .................................................. 42
  Recommendations ....................................................................................................... 47
  Aligning Brains, Averaging Brains, Subtracting Brains, Seeing Minds ................. 48
  That’s Psychology! ....................................................................................................... 51
  Anatomy and Talairach Revisited .............................................................................. 53
  MRI Anatomy ............................................................................................................. 54
  Talairach: a Digital Space Big Enough for Disagreement ....................................... 57
  Using Stereotaxic Space: Co-existing Versions of the Space inside the Skull ....... 58
  No one likes Talairach, but everybody has to use it .............................................. 58
  Warping Brains in Talairach Space: Individual, Variable, and Standard Brains .... 60
    Places in the Brain: Call my Name or Dial my Number ..................................... 61
    After Meaning Comes Significance: Statistics in Talairach Space .................... 62
    Towards a Model of the Brain ............................................................................... 64
    The Mercator of Brain Map Projections ............................................................... 65

Chapter 3 Maps of the Mind-in-the-Brain .................................................................... 69
  Seeing the Living Brain… Seeing One’s Life in the Brain ........................................ 69
  Maps and the Structure of Knowledge about the Mind-in-the-Brain .................... 70
  The Map as Experimental Metaphor ......................................................................... 74
  Definitions and Access to a New Territory ............................................................... 74
### Collapsing Atlases, Growing Databases

Chapter 6 Images at Large

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kinds of Digitalisation: Pipelines and Bureaucratic Organisation</td>
<td>166</td>
</tr>
<tr>
<td>Sampling, Variability and Individuality</td>
<td>168</td>
</tr>
<tr>
<td>Kinds of Biologisation: The Dimensions of the Mind-in-the-Brain</td>
<td>172</td>
</tr>
<tr>
<td>Evolution</td>
<td>172</td>
</tr>
<tr>
<td>Uniquely Human</td>
<td>173</td>
</tr>
<tr>
<td>Bounded Brain</td>
<td>175</td>
</tr>
<tr>
<td>Normality by Numbers</td>
<td>176</td>
</tr>
<tr>
<td>Metaphors of the Mind-in-the-Brain</td>
<td>177</td>
</tr>
<tr>
<td>A Materialist Science of Self?</td>
<td>178</td>
</tr>
<tr>
<td>A Factored View of Health</td>
<td>179</td>
</tr>
<tr>
<td>Representations in Science and Science as a Representational Practice</td>
<td>181</td>
</tr>
</tbody>
</table>

**Annex 1. Being There**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Choosing the Field</td>
<td>183</td>
</tr>
<tr>
<td>Going into the field</td>
<td>185</td>
</tr>
<tr>
<td>Speaking of imaging</td>
<td>187</td>
</tr>
<tr>
<td>Experiments</td>
<td>187</td>
</tr>
<tr>
<td>Analysis</td>
<td>188</td>
</tr>
<tr>
<td>Mapping</td>
<td>190</td>
</tr>
<tr>
<td>A second lab</td>
<td>191</td>
</tr>
</tbody>
</table>

**Summary**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Samenvatting</td>
<td>197</td>
</tr>
</tbody>
</table>

**Works Cited**

<table>
<thead>
<tr>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>201</td>
</tr>
</tbody>
</table>
List of Figures

Figure 1 Hearing Words, Seeing Words................................................................. 3
Figure 2 Talairach as shared convention in the field............................................. 8
Figure 3 Mixed Opticism and Digitalism............................................................. 16
Figure 4 The Brain of a Normal Population......................................................... 19
Figure 5 A probabilistic brain atlas..................................................................... 21
Figure 6 The volumetric "canonical brain", and the flattened cortex of the 2D brain 22
Figure 7 Various aspects of one method for transforming brains to a standard space 23
Figure 8 Digital Grid............................................................................................ 33
Figure 9 The "history of PET" according to one manufacturer................................ 34
Figure 10 Visual comparison of paper atlas and brain scan................................. 37
Figure 11 Head holders for marking the space of scans in the early eighties.......... 39
Figure 12 Translation of PET space into Talairach anatomical coordinates......... 43
Figure 13 Interface of an automated tool for the translation of PET into Talairach anatomy ............................................................... 44
Figure 14 Use of Talairach Space for Averaging and Subtracting Activations...... 49
Figure 15 Uses of the Talairach System............................................................... 56
Figure 16 The brain as a percentage of MRI and PET.......................................... 66
Figure 17 Stimuli in a cognitive subtraction experiment...................................... 79
Figure 18 Cognitive subtraction............................................................................ 80
Figure 19 The brain of subjects performing a task as new, practiced, and novel...... 91
Figure 20 Integration of the 'levels' of neuroscience............................................ 140
Figure 21 Galton's pictorial statistics: composite photograph of the military officer. 147
Figure 22 The structure of a probability atlas....................................................... 154
Figure 23 Probability and Variability Maps......................................................... 155
Figure 24 The Potential of the Integrating Atlas as Proposed by ICBM in 1997...... 157
Abbreviations Used

CT       Computerized Tomography
HBP      Human Brain Project
NIH      National Institute of Health
NIMH     National Institute of Mental Health, Washington, US
NMR      Nuclear Magnetic Resonance
MRI      Magnetic Resonance Imaging
aMRI     anatomical MRI
tMRI     functional MRI
PET      Positron Emission Tomography
SPECT    Single Positron Emission Tomography
SPM96    Statistical Parametric Map (followed by year of release), a widely
         used statistical analysis package
HGP      Human Genome Project
HGDP     Human Genome Diversity Project

Note on Images and Figures Used

Cover graphic of the brain with axes is reproduced courtesy of the Research Imaging Center, University of Texas Health Science Center at San Antonio. Many thanks to the other researchers and groups who shared their images, reproduced here in black and white. While colour would have enhanced their clarity, digital images are best viewed on a screen rather than in 2 dimensions on paper, and I encourage you to consult the following web pages for the full effect. All are very high quality sites and many of these are award-winning. For convenience, links are also found on my own website, at the Department of Psychology, University of Bath (http://www.bath.ac.uk/~pssajb/).

Thor Centre for Neuroinformatics
http://hendrix.imm.dtu.dk/image/imagehome.html

Van Essen Lab
http://stp.wustl.edu/surfaces.html

McConnell Brain Imaging Centre, Montreal Neurological Institute, McGill University

The Wellcome Department of Cognitive Neurology, Institute of Neurology
http://www.fil.ion.ucl.ac.uk/

ICBM (International Consortium on Brain Imaging)
http://nessus.loni.ucla.edu/icbm/index0.html

Probabilistic Atlases
http://www.loni.ucla.edu/~thompson/med1A_pics.html
Acknowledgements

The pleasure I experienced in writing this thesis is comparable to that of taking the perfect bite of a delicious meal. At times, I felt that skill and effort exerted onto raw materials combined to produce flavours and textures that mingled and complemented each other in just the right way—deeply deeply satisfying. I want to thank to those who taught me the basics of intellectual cookery: introducing me to ingredients and utensils, sitting down at my table, digesting the heavy meals, further suggesting spices, and giving me room to get on with the messy business. I am very grateful to Stuart Blume, whose work first brought me to Amsterdam. He supervised my efforts in pulling this material together, read and commented on numerous drafts and provided much appreciated encouragement—even from a distance while I pursued fieldwork, and in the final few months of the project after I had left Amsterdam. Science and Technology Dynamics was a privileged place in which to be during the period of my PhD, and I have fond memories of my time there. In particular, I would be very lucky to ever encounter again the mixture of insightful critique and supportive comment I found in the 'medical group' discussions, made up of Olga Amsterdamska, Ad Prins, Stuart Blume, Anja Hiddinga, Nelly Oudshoorn, Jessika van Kammen, Pascale Lehoux and several students. Ad Prins provided some very precious comments and suggestions while I was writing the proposal for this project—not to mention other gastronomical extravagances. I want to thank Paul Wouters for being such a critical and careful reader, and tell him how inspiring and energizing his enthusiasm for life and learning have been. Along with these colleagues, Willem Halffman, Donna Mehos, Olga Amsterdamska, Michiel van Well, Leen Dresen, Douwe Draisma, Bernike Pasveer, Abby Lippman and Nora Machado also taught me tricks of the trade and often provided just the right word at the right moment. My office-mate Anja was a wonderful companion in both big and small ways. We not only shared the day-to-day process of research and writing, but also developed the fine art of the 12 minute in-depth conversation—somehow all the big topics seem to have come up in our busy lives in the course of those years... and boy was I glad to have privileged access to an OWP!

The students from WTMC formed an interesting group of colleagues at summer schools and workshops (though I could never understand why some were so recalcitrant to be there and engage—maybe it was the food). Among my PhD cohort, the friendship of Jessika van Kammen, Ruth Benschop and especially that of Haidee Wasson, have been great contributions to the life of both heart and mind.

The Société canadienne d'histoire et philosophie des sciences/Canadian Society for the History and Philosophy of Science is worthy of mention, being one of the friendliest, most open societies I have encountered. I greatly appreciated the comments and curiosity of its members about my (albeit more sociological) work. My colleagues and students at the University of Bath provided a pleasant and supportive environment in which to finish this project. Special thanks to Helen Hansen and to Marianne Bonugli for assistance in
producing the manuscript in February when it seemed every second counted, and to Sally Jones for software support in the production of this latest version.

Many thanks to Shannon Aldinger, Christine Bernier and Patricia Thiel for being so relentlessly interested over the past ten years in the questions I have been asking of science and medical practice. I have found their curiosity about what I was investigating (and why) to be a truly great compliment, and look forward to many more years of discussing knowledge and politics with them.

Without the participation of many scientists from the field of neuroimaging, this research would simply not have been possible. I wish to thank Alan Evans, Peter Fox, Richard Frackowiak, F. Lopez da Silva, John Mazziotta, Geraint Rees, Per Roland, and many other researchers in labs and at conferences (to whom I promised anonymity), for generously talking to me about their work. Upon returning from my first visit to the field, I had the great pleasure of 'debriefing' with Renee Fox who was visiting the department at the time. Her encouragements to take my insights seriously are at the origin of the arguments made in chapter 4, the most 'ethnographic' of this thesis. Her intellectual inquisitiveness and generosity greatly impressed me.

The financial support of NWO, WTMC and EASST, and especially that of the Programme de bourses doctorales pour femmes dans des domaines non-traditionnels (province du Nouveau-Brunswick) is gratefully acknowledged.

And speaking of New Brunswick, this thesis also represents 'being away' for me. It meant a lot to me that friends visited from North America and helped bridge the distance, and that many others opened their homes and families to me when I first came to Europe. No wonder I missed mine--they're great in many many ways, but what they do best is unconditional love and support. Merci Claudette, Emanuelle, Geneviève, Gérard, Lucille, Ludovic, Marc, Martha, Maude, Sébastien. I also want to say thanks to my sister-in-law, Jacinte Roy, who maintained (e)mail contact, and, due to time difference, answered so many calls on Wednesday afternoons. I would have been even more homesick without her willingness to interrupt her work to ask me how I was and to give me all 'the news'. More thanks and a wink to friends and family for keeping up and being patient with my elaborate logistic constructions, as I moved and travelled across two continents, three countries and five cities in the course of this project.

I hope little Felix will one day hold this book--perhaps to read it, to look at the pictures or in the shorter term, to chew enthusiastically on it. If he does, he might be interested to know that the last bits of it were written by hands that reached over a big belly, and that the sections on development had taken on a very particular resonance by the time I finished writing. I cannot name, map, count, list or otherwise digitise all the ways in which Maarten Derksen has been supportive of this work. Know that I am grateful for them all.

*Bat* 12 July 2000
Chapter 1 New Views of the Mind-in-the-Brain

The last decade has been marked by great changes in the fields of psychology and neuroscience, and these changes have been highlighted by the declaration of the nineties as the Decade of the Brain in a number of countries, and the instigation of the Human Brain Project in the U.S. During this period, new views of mind and brain have been formed through the development of new technologies and new strategies for relating the mind and the brain. The objects of study of various disciplines and specialties have shifted in ways that have affected the greater cultural context, as well as institutional arrangements that rely on mind/brain distinctions, also implicated in these shifts in research. For example, through the use of brain imaging technologies, which show new aspects of mind and brain, rationality, responsibility and intent as key concepts in legal settings are being redefined (Kevles, 1997; Kulynych, 1996). Our own understandings of our subjectivity is also changing as we come to think of mental illness or learning disorders as having primarily a physical basis (Dumit, 1995). This thesis aims to trace these changes by focusing on a core project that arose between the mid-seventies and late eighties, and was consolidated during the nineties, namely ‘brain mapping’.

Brain Mapping and Representations

Brain mapping is a very heterogeneous research endeavour. One reviewer noted that the textbook ‘Brain Mapping: the Methods’ failed to provide a definition of what this is, leaving the reader to figure out, by default, that brain mapping refers to the diverse contents of the book. Even the label for this work has been the object of discussion: functional imaging, brain mapping and imaging neuroscience have variously been used to describe the stream of work that will be traced in this thesis. Significantly, arguments for particular labels are often formulated in terms of the need to associate or distance research from the technologies used. Functional imaging\(^1\) has indeed grown around a number of technologies constructed in the seventies, and relies to a large extent on the development of digital technologies. Among these many tools, positron emission tomography (PET) is often called the workhorse of functional imaging. PET’s development is typically presented by participants as bringing together research streams from physics, chemistry

---

\(^1\) I will use alternately brain mapping and functional imaging: both are meant to evoke the bringing together of brain and mind, but I take to have a slightly different emphasis: mapping highlights the labelling the brain in terms of its functions, while functional imaging stresses the technological possibilities of this particular type of scanning, especially in contrast to anatomical imaging.
and mathematical research. The following events are often mentioned: the first PET conference was held in 1978 at the Montreal Neurological Institute (Canada); a clinically-applicable 'early' PET was built around 1975 inspired by the work on CT scanner; 'mature' PET and the first commercially produced PET with cyclotrons were available by the mid-eighties.

While currently closely associated with neuroscience and cognitive psychology, PET was developed in nuclear medicine and neurology contexts (Kennedy, 1991; Kevles, 1997). It was first applied to measure cerebral blood flow and metabolic abnormalities in the brain, such as high-energy consuming tumours in the early eighties. It was also used for pre-surgical evaluation of epileptic patients, a clinical practice in which a different type of mapping was often performed during surgery. Later used in combination with other imaging technologies, PET studies in brain mapping research allow the localisation of cognitive functions to particular areas or groups of areas in the brain. The experimental methods for localising cognitive activity with PET were developed in a series of studies in the course of the eighties (See Figure 1, on page 3). These developments will be discussed in detail in a subsequent chapter.

---

2 Depending on whether they emphasise technology or brain mapping, researchers will trace the history of radioactive substances and their detection, or that of using blood flow to measure metabolic activity. See Ter-Pogossian, 1992; Phelps, 1991; Kennedy, 1991 for first, Raichle and Posner, 1997 for emphasis on second. Another element in the history of PET which would deserve further investigation is the link to national nuclear research programs and government support of this research as a peaceful application. See Kevles, 1997, especially pages 208-11, and Paul Cho. “U.S. DOE Programme of Support for PET and Nuclear Medicine”, 1992.

3 The first commercially built tomograph was produced by EG&E, Oak Ridge Tennessee in 1978. One reviewer places the beginnings of PET “shortly after the moment of creation, the Big Bang...From this boiling sea of nuclear reactions emerged positrons, electrons and the annihilation radiation signal used by today’s PET systems” (Rich, 1997).

4 A number of factors distinguish clinical, presurgical mapping and "cognitive" types of study, such as a focus on the 'normal' as opposed to diseased brain, and the involvement of non-clinical psychologists. These types of mapping have a times been pursued entirely separately, though some institutional arrangements fostered cooperation, for example where a tradition of clinically-based research in brain mapping existed. Certain projects under the aegis of the HBP also aim to foster such cooperation, though up to now one or the other view tends to dominate (compare for example Ojemann et al and Mazziotta et al in Neuroinformatics). Some areas of brain mapping are endeavouring to make their tools clinically significant.
This is the psychologist's rendering of brain mapping. The space of the brain is clearly present, the outline marks the space in which function occurs, but the most prominent aspect are the floating rainbows, which, though anchored in the brain, most dramatically depict function against function. In the same way that the nineteenth century physiologist Marey's visual measurements removed depth, and all other elements not involved in motion and temporality, so this image, which became the emblem of mapping, shows the cognitive brain. The rainbow acquires an iconic role in showing activity, while structure is depicted as white outline (as above) or in the grey scale of x-ray tradition, with some variations to other (single-tone) scales, such as 'hot metal'.

Reproduced courtesy of Dr Marcus Raichle.

But PET is not the only tool involved. Since about 1992, the development of functional magnetic resonance imaging technology, (fMRI, the use of an MRI scanner to measure 'function') has also changed the above picture. fMRI scanners are more common than PET scanners, since they are more widely used for clinical imaging, and less expensive to run. The possibility of doing brain mapping studies has therefore been extended to many more centres, leading to a new kind of competition in the field. Some PET users have expressed fears of a band-wagon of imaging studies done by non-experts in functional imaging, while the 'death of PET' was also pronounced--fMRI does not require a cyclotron, and is considered less invasive than PET scanners which require the administration of radioactive substances to subjects. Other technologies have been brought under the label of brain mapping technologies since the mid-nineties; the latest Human Brain Mapping Conference Brain Mapping course dedicated time to fMRI, PET, trans-cranial magnetic stimulation, MEG and EEG, and 'anatomy' as key components of the brain mapping armamentarium. A common motif in the use of these many technologies is that they are variously coupled to provide representations of both activity and structure, as maps of function in the space of the brain. The results of multiple tools
are therefore combined to produce a complex object—the map of activity in the brain, from merging types of data.

Around this research, a recently formed community shows some of the earliest traditional signs of 'professionalization' or discipline formation. The International Conference on Functional Mapping of the Human Brain has been held since 1995, when the first conference was organised as a satellite meeting of the Society for Cerebral Blood Flow and Metabolism. The annual meetings attracted about 1000 researchers. Two journals have been set up and oriented to publishing brain mapping research: *Human Brain Mapping* (1993) and *NeuroImage* (1992). The publications of monographs and textbooks on brain mapping is also quite recent. Besides *Images of Mind*, published as a Scientific American Paperback (1994, 1997), and addressed to "a broad audience", other textbooks on brain mapping appeared in the nineties. Yet, a great amount of diversity remains in many aspects of this research, and up to the late nineties, the Association has been deliberately 'conservative' in its activities, concentrating on organising the yearly meeting and course. Disciplinarily, almost no one has been 'trained' in this 'field' (Fox, 1993), and large interdisciplinary teams are involved in running experiments— motley crews of physicists, statisticians, psychologists, neurologists, etc. Such diversity can also be observed in terms of scanners and software used. Even before other technologies were included in mapping, throughout the eighties PET scanners could be considered 'little big science', with no two scanners and cyclotrons being the same, and until the release of a 'package' for data analysis, the software used was also quite diverse. As well, PET is usually used in combination with other imaging technologies (CT or MRI), and combinations may differ per institution. Furthermore, because of the costs and complexity of purchasing and running the scanners (Frick et al., 1992), alliances with several research and clinical groups have been the rule, so that no two centres have had similar overall research agendas.

Brain mapping has been amply discussed, praised and contested by researchers in terms of its results and of its contributions to understanding the mind/brain dichotomy. In reaction to claims of being able to 'see the mind', brain imaging has sometimes been (pejoratively) presented as positivistic, an endevour limited by researchers' failure to address the meaningful content of what they are imaging:

---

1. The 1999 meeting in Dusseldorf attracted 1093 abstracts, and the electronic mailing list of the organization contained 830 email addresses.
2. A few publications on brain metabolism and PET came out in the eighties, generally directed to clinical application. Textbooks oriented to brain mapping appeared in the nineties: *Brain Mapping: the Methods*, 1996; *Neuroinformatics*, 1997; *Human Brain Function*, 1997. These books were only just appearing as my own project was unfolding. The lack of these types of materials at the beginning of the project, as well as lack of 'secondary' sources, were strong motivations for going into the field. Having to deal with scientific articles directly sometimes felt like I was doing things the hard way, though the feeling of being on the cutting edge also kept me ploughing through the material. I am particularly grateful to Joe Dumit who shared some of his work on PET while I was considering pursuing this project.
3. Arguments have been made in the 'town meetings' of yearly conference for the need to have a strong organisation which would counter the molecular biology lobby (Boston 1996), and to stimulate and possibly enforce the use of standard 'spaces' and nomenclatures for reporting results to increase the 'coherence' of research (Dussedorff, 1999).
"One must think about what it means to the brain to be part of a human subject paid to lie in some machine while performing more or less stupid tasks (and most of the paradigms studied in the actual brain function/cognition projects with imaging are so simple that the brain will never be confronted with them in real life) (Schmitt, 1995)."

In this view, mind is the meaning of brain processes, and this remains outside reach of these imaging experiments. For others, the successes of imaging are at best marginal, exploring only what is at the edges of mind. A reviewer states that while the authors of the popular book on functional brain imaging, entitled Images of Mind,

"seem to have gone out of their way to make the results of PET scans seem humanly and psychologically meaningful, ... this effort can most generously be called a limited success. PET scans have indeed provided us with ‘images of mind’, but only of very few simple aspects that, by and large, really do not tell us very much about how the mind as a whole behaves (Goertzel, 1995)."

This reviewer further hesitates as to what these results address, and goes on to say that “at present, however, the scans...feel more like ‘images of brain’ than ‘images of mind’ (though the latter is also a perfectly accurate description) (Goertzel, 1995).” While the imaging technologies have not yet delivered, and though they leave the reviewer unsure as to the status of the object they show, (mind or brain or are these both the same), the promise of these experiments does not leave him indifferent, as becomes apparent from the rest of his review. Indeed few have remained unmoved by brain mapping, reacting to its claims, costs or vivid images. 

In more enthusiastic evaluations, research using brain imaging technologies has been widely presented as an exploration of mind in scientific (because material) terms. ‘Consciousness research,’ often labelled the hardest question in cognitive science research, is said to be making a comeback; the contribution of imaging research makes it into an empirical discipline. Many discussions setting out research agendas have defined mind and brain, subsuming the former to the latter:

"Another term for this complex of cognitive processes that are in many ways uniquely human is ‘mind’, which is not to be taken as some mystical entity but rather as a description of the functional properties of our brains that render us human. Thus the study of human cognition and perception is in a very real sense

---

8 See Tom Wolf (1997) “Sorry but your soul just died”, and Fodor’s ‘diary’ in the London Review of Books (1999), for two particularly colourful commentaries. I thank Michael Lynch and Stuart Blume for bringing these to my attention.

9 The point has been made in reviews (Russo, 1999) keynote speeches (Tulving, 1997 Conference (fieldnotes) and interviews (Schulman, 1996), and a number of popular science books (Dennet, 1991: Rose, 1999). Gregory and Miller (1998) point to this wave of books about consciousness as an example of how science marks certain new domains of research as properly scientific.
the study of the functional properties of the human brain... One aspect of the study of human cognition and perception is the use of various non-invasive techniques, such as PET, MRI, ERP, and MEG to discover the neural correlates of human cognitive and perceptual activity (NSF. 1991)."

The scare quotes around the word mind, and the prescriptive formulation warning against mystical views, are indicative of tensions in brain mapping research (which will return in the course of this thesis), between a materialistic philosophy of experimentation and dualistic notions limiting what can be known about the mind. Indeed the healing of a Cartesian breach has been a recurring trope in discussions of functional imaging technologies; these scientific experiments move from brain to mind as though the philosopher’s division had never existed.10 Taking an even stronger view, some have announced the death of the mind:

“...The time has come where brain function, from emotion to mentation, imagery, intention and so on is definable, in the relatively crude terms that we can define it now, in the substance, the material substance of the brain. So things like soul and mind and so on become useless, no longer of any use in scientific discourse (Senior Researcher, trained as a physician).”

During the same period, there have been appeals to scientists to accept that the brain has "dimensions", along which it can be studied, though some are “repelled by a reductionistic approach which has proved so successful in understanding other organs of our bodies (Koshland, 1992). “

The working brain, visible in a PET scan, is therefore presented by researchers, in turn, as touching the hard core, or as (literally) mindless reductionism--with less extreme versions of each view in between. The notions of mind and brain are important concepts for researchers in psychology and neuroscience, which determine what can legitimately be claimed, questioned and investigated in the course of research, as well as delineating who is qualified to pursue these investigations. The few arguments presented above provide a glimpse of a partial reconfiguration of the mind and brain dichotomy through brain mapping research. The consolidation of the biological basis of mind in relation to brain mapping is especially of interest here.

Bounding the brain and studying it according to its ‘dimensions’ requires a number of shifts and innovations in social and technological arrangements, which are all the more complex, as the brain becomes the place from which to study the mind. Brain mapping research is often discussed in terms of a ‘window onto the brain’, through which

---

10 See chapter 3 for discussion. The dichotomy is addressed particularly intensely in an issue of Behavioural and Brain Sciences, dedicated to imaging research. Brain and Behaviour is a journal dedicated to the discussion of particular themes through peer comments from a wide range of prominent researchers in psychology and related fields, and the sheer number of peer comments which address brain mapping as a mind/brain issue is impressive. See among these “Tough Times for Dualists” and other articles in Posner and Raichle (1995).
the workings of the brain termed the mind can be observed. The assumed transparency of
the technology participates in important ways in the discourse of collapsing mind into
brain. Accessing the mind is presented as a matter of developing a technology to look at
the brain, to penetrate the space inside the skull. But technologies do not render nature in
any self-evident way. And when they seem to do so, it is the result of complex processes.
These processes are all the more multi-dimensional when, as mentioned, a number of
technologies and disciplines are involved, as is the case with brain mapping.

Rather than showing the development of brain mapping as the desirable or
harmful evacuation of one term of a mind/brain dichotomy through technologically-
mediated discoveries, I will show how these objects are recast. By asking ‘what is the
brain’ and ‘what is the mind’ being investigated through these technologies, it becomes
clear how traditional boundaries come to be blurred, and how these objects come to be
superimposed onto a map. I will argue that in the course of developing a mapping
practice, a different object, the mind-in-the-brain, is constituted.11 Recasting the question
in these terms not only de-essentializes scientific categories, but it also points to the
importance of processes of institutionalisation and technologies in the constitution of
these objects. This thesis addresses the development of scientific knowledge and the very
contents of a new stream of research, as shaped by intertwined processes of biologisation
and digitalisation. It does so by considering brain mapping as a new arrangement for
seeing, an emerging techno-scientific project in which representational practices play a
key role.

It is difficult to speak of functional imaging research as a speciality or discipline,
or to trace its development according to a single technology or research area. The object it
examines is also contested. A thread linking various developments can be found,
however, by considering these developments as the constitution of brain mapping as a
representing practice. The importance of building and sharing representations can be seen
at many levels of functional imaging work and its importance stressed by participants. For
example, the growth of this stream of research was recently evaluated using citation-
analysis, which takes a shared representational convention as an indicator of work done in
the field. (See Figure 2). From the point of view of the editor of Human Brain Mapping,
having a reference to Talairach atlases means working on the topic of brain mapping.12

---

11 I offer this neologism as a way of underlining the translations and transformations performed (especially
by cognitive neuroscientists) in order to form their object of study. It also highlights how these scientists
present the specificity of their claims in addressing the neural correlates of cognition. The term arises in a
context where many scientists are rejecting the word ‘mind’, while still invoking the wonder of what makes
us human. Hence my own need to have these terms of mind, brain, and mind-in-the-brain, in order to
analyse how the subsuming of mind to brain is still actively discussed, and made into a special claim in
relation to a pre-existing tradition where the terms and concepts are separate.
12 This marker was also used in documents of the International Consortium for Brain Mapping (ICBM), in
an editorial for Human Brain Mapping (Fox, 1997) and in communications with and publications of the
Human Brain Project.
In terms of the work performed in the lab ('what functional imagers work with') Annex 1 contains my account of discovering the importance of representations through fieldwork. There is very little 'wet' work in brain imaging: human subjects appear briefly, for a few hours at specific times, and the manipulation, analysis and interpretation of representations form the overwhelming majority of the work performed in the lab.

Another sign of the importance of representations can be found in discussions and reviews of journals in which functional imaging research is to be disseminated. The editor of *NeuroImage* promises attention to representations:

"The care we give to reviewing, typesetting, and producing the manuscripts will be surpassed only by our commitment to visual integrity of the illustrations (Toga, 1992)."

In the same vein, reviewers of journals evaluate the ability of journals to carry the representations produced in this research—whether colour images can be reproduced, whether authors are charged for these and what the quality of representations are (Cohen, 1997, reviewing *NeuroImage*). For reviewers, the claims of brain mappers are best supported when journals can render colour maps, the representations in which these claims are embedded:

"The large format and high-quality reproduction allow the dramatic colour images—a hallmark of the field—to be shown to magnificent effect (Haxby, 1995, reviewing *Human Brain Mapping*)."

The corollary of this alignment between a material support that accommodates the elaborate representations and brain mapping research also holds. When the production
values praised above are not included in a journal’s profile, then this is taken to exclude brain mapping investigations. A reviewer of a new journal on “laterality” assumes that the journal will favour the “phenomenology of laterality” and “speculations about its neurobiological underpinnings”, rather than clinical work and imaging studies:

“This inclination is reflected in the small format of the journal (which precludes the large glossy figures that are now routine for imaging studies) (Purves and White, 1995)”

Representations are therefore acknowledged as important for the field itself, in terms of making and sharing its object(s) of research. The importance of developing representations and conventions for making and interpreting them will be shown in detail in subsequent chapters. Undoubtedly, representations permeate all scientific work (Latour, 1990; Lynch, 1990); a focus on representations and inscriptions in science studies purports to make visible the dynamics of Western scientific work and its successes. The argument I am making here takes representations as a starting point in a slightly different way; it takes representations to be important for understanding brain mapping work in particular. In a community-in-formation, where the material and institutional conditions vary, where various disciplines interact, and where the scope of the common project of ‘mapping the mind’ is far from settled, researchers recognise each other’s work in terms of the representations produced, and they evaluate their own successes in terms of their ability to produce maps and to have their results circulate in terms of representations in journal and databases.

Representation will be examined as a communal activity, not primarily as a cognitive one. Looking at representations is a way to get insight into the conventions of a group: into its “instruments, graphic inscriptions and inscriptional processes” (Lynch, 1990). Representations form the empirical materials obtained through imaging technologies (scans), the experimental strategies and knowledge claims (maps), define the epistemics of functional imagers (their view of what they do) and are part of strategies for establishing brain mapping as important in neuroscience and its clinical applications (atlases).

The few markers of development of this community discussed above point to the large investments in representational techniques that provide brain mappers with their object. But, to recast Hacking’s (1983) terms, researchers do not want to be seen to be only ‘representing’, in the sense of passively observing, but as also ‘intervening’, experimenting with the brain and mind. Their object of study, being so powerfully visually representational, is the source of anxiety. A search for ways to overcome this, by highlighting the search for principles of brain organisation rather than maps as

13 Not only representation but also vision can be considered in professional terms. The socially negotiated nature of perception has been analysed in settings where proper visual perception is taught (a biology or haematology lab or an archaeological field) or where participants must co-operate in order to see anything at all (for example marine explorations where boat, camera and marine life have to be aligned). See Lynch (1985) Atkinson (1995), Goodwin (1994) and Goodwin (1995) respectively for each of these studies.
representations, is a growing concern in recent brain mapping research (Friston, 1998). Furthermore, the central role of representations in this work underlies an important tension in brain mapping research, which will be addressed in detail in a later chapter.

**Representations in Brain Mapping: Physical Minds and Virtual Brains**

Brain mapping, as a new high tech arrangement for seeing inside the body, is involved in two entwined processes, namely biologisation and digitalisation. Brain mapping inscribes notions of mind onto the body, but does so through the mobilisation of a set of technologies and manipulations involving complex digital spaces. Each process will be discussed here separately, in terms of the intellectual traditions which have construed them as categories for analysis, but will be discussed as interacting in subsequent chapters.

**Self, Embodiment and Biologisation**

Many scholars have analysed the ways in which the body is explored and marked, and made into the locus of power in modern and post-modern culture. Complex interactions between the creation of new objects of scientific study, new institutional arrangements and new modes of 'governmentality' often revolve around the constitution of representations. Brain mapping, as a new stream of research, seems to be constitutive of new representations, recasting the terms in which not only the social and the somatic, but also the mental and the physical are understood. Phrases used to describe brain mapping research, like “mapping thoughts”, “the mind in action”, or “the biology of madness” point to brain-based conceptions of mind and its diseases—arguably, formulations which contrast with the more psycho-dynamic views which were dominant two or three decades ago. The emphasis on finding new physical traces of the mind inscribes brain mapping in a process of biologisation. Notions of self and of mental illness have long been tied to the concept of the mind. When mind is linked to the brain, this object of study is accompanied by shifts in notions of self and mental illness. As the mind comes to be known through the body in novel ways, then a different configuration of the self arises, with a different relation to systems of knowledge and power.

Analyses which address the recasting of social relations in terms of the body have been inspired by Foucault’s work on the relation between knowledge and institutions for (clinical) medicine, the penal and military systems or the management of insanity (Foucault, 1975; 1976a; 1976b). A common theme in this body of work (again, following a Foucauldian theme) has been to analyse the move to embodiment. This can mean inscribing onto the body the regimens of health, hygiene, military discipline, morality, as well as dysfunctional opposites: disease, insanity and inefficiency. Measurements of heights, strengths, weights, temperatures, speeds, and shapes of large numbers of conscripts, workers or patients have led to particular understandings of normality and abnormality. Thus, the argument goes, difference came to be a mark of the body at the end of the 19th century, “the somatic territorializing of deviance” as Urla and Terry (1995)
have coined it. Such critiques sometimes posit embodiment as essentially problematic (more on that below). But for the purpose of this thesis, the strength of this approach is in highlighting the link between the body and the social, between the individual and populations, through the constitution of representations:

"...what we know to be bodies are always representations; what matters is that scientific and popular modes of representing bodies are never innocent but always tie bodies to larger systems of knowledge production and indeed, to material and social inequality (Terry and Urla, 1995)."

The way in which representations circulate and tie the body to these systems of knowledge will be discussed in the next section. The argument has also been made that these large systems of knowledge are actually getting larger, increasing the extent to which the biological as the domain of life is used to define relations in social systems (van Dijck, 1995; Rabinow, 1992). The Human Genome Project and molecular biology have been analysed as the source of geneticization as a particular kind of biologisation, the trend towards the attribution of a genetic definition of conditions (Lippman, 1992). This trend transforms not only social relations in terms of biological definitions but also generates modes of social interaction based on biology, what Rabinow has termed bi-sociality. In this context, there is a partial

"move away from face-to-face surveillance of individuals and groups known to be dangerous or ill, ... toward projecting risk factors that deconstruct and reconstruct the individual or group subject. This new mode anticipates possible loci of dangerous irruptions through the identification of sites statistically locatable in relation to norms and means (Rabinow, 1992)."

The use of formal and bureaucratic tools (surveys, files, tests) are an important component of this process, which is "non-subjective in a double sense: it is objectively arrived at, and does not apply to, a subject in anything like the older sense of the word (that is, the suffering, meaningfully situated integrator of social, historical and bodily experiences (Rabinow, 1992). " This has been termed the "technocratic administration of difference" (Castel, 1981), which focuses on sets of factors which it represents and finds in/significant. Castel, perhaps more than Rabinow, aim to explore but also to critique these changes in scientific and medical arrangements.\(^{14}\)

\(^{14}\)Within this category of biologisation, Castel's notion of the "technocratic administration of difference" further qualifies the process, though this label too can be further defined in terms of, for example, a digital, database-reliant mode of administration. Amsterdamska has demonstrated that this process varies between settings in terms of cognitive models and experimental strategies (Amsterdamska, 1998). The argument is further spelled out here:

"It has often been said that the modern biomedical sciences are reductionistic and that the chemical understanding of physiology and pathology has become dominant in 20th century bio-medicine. It is questionable, however, whether we can speak of a single reductionism rather than a variety of potentially incompatible reductionist analytical frameworks. It is one thing, for example, to reduce disease to a failure in the functioning in the immunological system, quite another to see it in terms
While having blossomed into a large area of academic inquiry, the theoretical and analytical moves which point to changes in notions of ‘the embodied subject’ seem to lead to a conundrum. Not that odd juxtapositions do not have their place in end-of-millennium theorising; purity is no longer a criterion. But, coherence, if not purity, might be a reasonable goal; paradoxes may still be preferable to contradictions. The question can then be posed as follows: How does one perform a critique of such a move to post-disciplinary or post-modern notions of the body, if bodies in modern society are said to be properly understood as representations? Constructivism, because it rejects the possibility of an un-represented body, has often been accused of being incapable of such evaluative assessments. How is it possible to make the constructivist point that bodies are made and unmade as representations, while also maintaining a sense of what is gained and what is lost in the various configurations of modes of representation? In other words, how can a notion of the body or of the self (on which such a critique would rely) be maintained, without appealing to unmediated versions of these, which would imply finding the body outside representation and technology… Van der Ploeg (1998) suggests a metaphor to understand the relation between these registers. Modernist notions of self and post-modernist moves towards multiplicity, diffuseness and a breakdown of boundaries (human/animal, biological/material, etc) can be seen as two sides of a coin. The notions of normal bodies can be then critiqued as having served to maintain Subjective Western Man, and never having existed in nature to start with. The way deviance from this model is established can also be shown to marginalize and disenfranchise ‘others’ from full participation in the state as citizens, in the market as labourers or owners, or as possessing a fully-fledged autonomous self in the case of living wills and pregnant women (Davis, 1994).

At the same time, it is also possible to view post-modernity as a co-existing, alternative discourse, in which there may be powerful positions. These are appearing ‘kitty corner’ from regular bodies which we sometimes only too happily inhabit, as the institutions that sustained and were sustained by Man are pulled, bent and otherwise exploded out of their original shape by the new configurations of world economies, cyberculture, coalition politics and enhanced bodies that go from substandard (‘handicapped’) to better than most (Haraway, 1991). In such a world, flexible bodily boundaries, inchoate personhood and multiple alignments may be better ways to gain access and exercise power than the proper correspondence to the norm. But, from a pragmatically political perspective, Van der Ploeg (1998) makes the powerful point that if only those traditionally excluded from notions of personhood take up the labels of post-modernism, this may not challenge the categories used by those currently in power and simply dissolve any political action that was arising at the margins.

of a vitamin deficiency and a different one yet to understand it in terms of genetic defects (Amsterdamska and Hiddinga, 2000)."

The analysis developed in this these focuses on the interactions of biologisation and digitalisation, as a particular configuration of bio-techno-power.

Mol, Annemarie, Personal communication, WTMC Winterschool 1998
Again, the question posed here is then how to avoid the conundrum of oppositional discourse which appeals to a romantic notion of the natural body in order to critique an institutionalised one. Van der Ploeg provides a philosophical answer: Post-modernism can serve as a powerful stance to highlight what and who is excluded. And while the contingency of representations of the body itself cannot be critiqued, categories of modernism are not powerless because contingent, she reminds us. We are, most of the time, (still) predominantly interpellated by institutions on the basis of modern bodies. From an anthropological point of view, Rayna Rapp (1997) proposes two empirical strategies to solve a similar conundrum in her study of ultrasound: to explore the meanings attached to new technologies by a variety of subjects, and to try to open up the context in which debates are pursued, shifting these debates from medical/scientific framework to a wider cultural/social framework.

The first strategy has been applied to brain mapping in a few studies. Dumit has explored what it means for the category of person to be partly constituted through novel digital imaging of the brain. This analysis reminds us that the stakes are indeed high, when the basis of the self is addressed. Dumit offers this declaration of a biological psychiatrist, whose review of PET research begins with the following words:

"In the 1970s, the anti-psychiatry movement almost had us...but now we have proof (quoted in Dumit, 1997)."

With the “proof” provided by PET, biological psychiatry puts anti-psychiatry on trial, and it puts scans of brain function in the witness box.\textsuperscript{16} Dumit goes on to note that even in cases when non-biological therapies are valued, they are meaningful in terms of the brain, in the same way pharmaceutical treatments are understood:

"the brain remains the bearer of mental illness, but has now become an intersection for social and biological influences (Dumit, 1997)."

The brain is indeed an intersection for therapeutic interventions, and an obligatory point of passage, through which the physiological effects of drugs as well as social and cultural phenomena are to be translated. Also in a psychiatric context, Dumit notes that patients and their families may find that brain scans enable them to destigmatize their condition, and to posit a potentially healthy self, afflicted with a sick brain. Other work on the contextual meaning of these images of brain function show a great deal of hope invested in PET scanning, likely means of ‘testing’, and offering the possibility of distinguishing normality from abnormality. The desire for an objective answer to health and disease is focused on the body, and on the ability of technology to provide particularly objective answers (Dumit, 1993; Beaulieu, 2000). Other meanings of brain scanning, particularly those of cognitive psychologists, neurologists and neuroscientists will be encountered in the course of this thesis (especially in chapter 4).

\textsuperscript{16} This also happens literally. See Dumit (1997), and Kulynych (1996).
But mainly, this thesis will further follow the second strategy suggested by Rapp in order to discuss technoscience and embodiment. Rapp, as mentioned above, proposes the recasting of debates about technology from a medical/scientific context to include a more cultural/social one. Some of her efforts at doing so address debates about the use of ultrasonic technology, but present this technology as black-boxed, the object of a factual description, so that technology is not explicitly brought into the debate she wishes to broaden. My own attempt to recast debates about brain mapping will closely follow how various uses of technologies and the knowledge they bring are developed. This contrast in approaches is perhaps most typical of the kinds of moves specific to science studies, which open up the boxes of knowledge and technologies left closed by other disciplines such as gender studies or medical anthropology.

I also wish to note here that such concerns are not totally foreign to the preoccupations of brain mappers, though they tend to remain very marginal, in terms of time, and effort invested in dealing with them, besides simply flagging them. For example, in a special issue on biomedical imaging, the following issues were noted: the growth of imaging in biomedicine increases the role of computers, opens up new fields of study and creates new responsibilities for researchers. Deploiring that images seem dangerously transparent and require vigilance;

"Countering these dangers means an increased awareness that images are constructs that include just as much ‘noise’ and require just as much care as any other technique (Crease, 1993)."

But besides occasionally noting that imaging is especially likely to lead to epistemically irresponsible behaviour, development of these techniques is labelled progress, and little is made of these pious remarks. These themes are brought centre stage in this thesis.

**Digitalisation**

Having sketched the approach to discussing the representation of bodies, another aspect of brain mapping can be addressed. The particular biologisation of the mind involved in brain mapping is entwined with the development of a relatively new context for making representations: the use of digital tools. If new representations are powerful in reconfiguring key dichotomies and interventions in mind and brain, this power is constituted in a large part by the possibility of making and circulating these representations. The development of brain mapping intersects with the growth of digital media. The dynamics of the constitution and use of new media constitutes the kind of topic traditionally significant for science studies, not only because it becomes a new support for scientific knowledge, but also because of new possibilities it offers in research. The ‘digital’ furthermore reorganises physical spaces in which scientific work
takes place (See Annex 1 for some of the material consequences for lab work of a focus on the digital). The consequences of the ensemble of practices, technologies and institutions which can be loosely labelled ‘digital’ will be discussed theoretically here, with emphasis on the consequences for representations. Two main aspects are of interest: new objects built in digital contexts, and new modes of circulation of digital representations, often mutually constitutive aspects.

Digitalism offers a particular configuration of epistemology, representation, and laboratory work, which become visible when contrasted to an optical form of these, as demonstrated in Michael Lynch’s work on topical spaces (1991). A topical space is both a symbolic and physically constituted space which is articulated in relation to technological organisation. Such an analysis ties an epistemological framework to a particular topical space. In other words, by being able to analyse a particular site of knowledge production, in its symbolic and physical features (which are affected by the technological organisation of the site), the very knowledge that emerges can be characterised.

Lynch’s starting point is the context of knowledge: where is the lab? He notes how the scientists peering into instruments inhabit a world that does not make sense to him as observer, yet does not seem to them to be a world separate from the everyday world. How then is the space created where things are perceived that are not readily available to all, yet seem to be in continuity with the ordinary world? Lynch suggests a limited Foucauldian notion of the organisation of the locale of the lab, where language is not determinant but rather plays a participatory role. He states:

"it would be incorrect to say that any particular application of language creates a space of operations: rather, any such application participates in a contexture of activities in which a space is organised (Lynch, 1991). "

In order to elaborate on Merleau-Ponty, who does not consider historical of technological variations in this encounter between body and world, Lynch draws on Foucault’s articulation of how “embodied spatiality” is affected by technological and textual mediation of perception. Specifically, two orders of spaces are discussed by Lynch, optimism and digitalism. These are worth considering in some detail here, since they demonstrate how new technological possibilities and new representations might be linked to discuss the context of knowledge about the brain.

Opticism is a set of constructs used to describe perception (an image of the world is projected on the back of the eye) and which provides much of the vocabulary used in epistemology. The following features of optimism form the “‘epistemic’ conditions of embodied action in particular technological complexes (Lynch, 1991):”

1. Ocular vision provides the paradigm of perception and observation.

17 A question that also arose in my fieldwork, on a more pragmatic level (See Annex, page 191), when I tried to find the place of work. The spaces I consider are not only individual labs but also how such outposts of spaces are constructed to enable cascading to extent. See especially chapter 5.
2. Visual field and viewer’s images are clearly distinguished along Cartesian lines. (there is an object out there and an internal image inside the observer).
3. The viewer’s “eye” becomes a singular point or aperture toward which a field is oriented.
4. The field is framed by a window, often represented as the outer edge of the cone of the rays.
5. The relationship between eye and object is transacted through a converging arrangement of linear rays. This arrangement limits forms and axioms of Euclidean geometry with the mechanisms of vision.
6. A transparent lens and/or reflective mirror mediates the linear transfers of rays into...the eye’s image.
7. A point by point correspondence obtains between image and object....
8. The model for vision supplies a vocabulary and sets of topics for a more general epistemology.

Figure 3 Mixed Opticism and Digitalism

This drawing wonderfully illustrates Lynch’s definition of opticism (especially points 2-7). It is a reworking of a drawing of Descartes’ theory of the formation of images on the retina (published 1622). A brain’s outline has been added inside the head and a small image of the brain slice being ‘seen’ is drawn on back of the head. The drawing further illustrates a clumsy encounter of opticism and digitalism: the object of vision is presumably a digital fMRI scan on which visual activation is represented, a scan of the visual cortex’ localisation appearing on the visual cortex. This visual pun further invokes the healing of Descartes’ split discussed in the introduction: here the mind shown as the brain knows the mind, by seeing it represented on the brain.


Thus, opticism coordinates spaces and practices: optical instruments, representational technologies, a theory of optics (Lynch, 1991). All these are part of a way of organising, conceiving and articulating the relations between the subject and the object, which seem to be challenged by digitalism. Lynch is not interested so much in the epistemological essence of knowing, as in the scripts that may be embedded in opticism: “what it expresses is a set of instructions for performing actions in accord with the various optical knowledge-production machines; a disciplinary compliance on the part of the subjects in those systems (Lynch, 1991).”

16
Systems within opticism, it can be repeated, deal with the lensed instrument as paradigm. In contrast, digitalism focuses on the play of fingers on a keyboard instrument, in contrast, though not in contradiction to opticism; the two modes co-exist as shown in Figure 3. A digitalist version of perception describes it as the deciphering of a psychophysical code. Lynch draws up a list of features associated with digitalism:

1. pixelated space: digital space is mathematised in terms of atomic details
2. arbitrary code: the code does not resemble anything
3. manipulable details: the elements of the keyboard have no inherent tie to an object; they are places for the fingers to strike in the course of an expressive action.
4. diachronic organisation: an order emerges from the play of signs in a series rather than from a point by point correspondence between an image and object.
5. an equivalence of ‘qualities’ and ‘quantities”: no distinction between form and content.

Thus, digitalism is an explicitly simulated or constructed space. Phenomena in a digital context are not in a particular representation: research scans do not have the status of snapshots in this digitised world, but are constantly recreated in the processing of electronic data. While ‘construction’ of representations may be more evident, this does not mean that any and all constructions are possible. Therefore, brain mapping evolves in a digital context, sometimes in opposition, sometimes in interaction with the optical mode, and the possibility of particular types of construction it enables. Digitalisation of the brain might have consequences not only in so far as it constitutes a way of knowing, but also as it is intertwined with a new view of the brain, a new research paradigm around it, and a new set of tools for applying this new knowledge.

In terms of digital representations specifically, much remains to be investigated about this relatively new mode. The comparison of opticism and digitalism seems fruitful, and points to the possibility of using the categories of representations from an optical topical space to contrast those of digital representations. A major effort in highlighting

---

18 As Lynch also shows, this construction in digital imaging may be hidden in favour of appearing to offer an optician approach. In some instances, digital images are used to evoke photographic realism, an optical presentation of digital images. The astronomers also use the conventions of photographic realism to give a ‘qualitative’ appreciation to funding bodies or lay people (Lynch, 1991). They allow their images to stand as pictures, but do not spell out how the epistemological assumptions of digital representations might contrast with the optical understanding of the lay public.

"in contrast to the pointillist or impressionist artists, who topicalized the compositional elements of painting, thereby exploding the established conventions of pictorial realism, astronomers tend not to bring out fully digitality’s distinctive contexture. As a consequence they act as a community of the wise (Goffman, 1963), sharing a secret understanding of non-apparent qualities while putting on a front for the sake of prevailing standards of taste and decorum (Lynch, 1991)."

Much more can be said about the choices made by astronomers and how these serve to establish professional identities and reinforce boundaries between science and the public (see Chapter 4).

19 This strategy has been used in other analyses, by Cartwright (1997) to compare paper and digital anatomy, for example. While this approach is less likely to fall into the ‘hype’ of new media, its
the importance of representations in scientific practice has been the Latourian notion of inscriptions (Latour, 1985). It aims to provide a correlate to the efficacy of Western science and technology since the modern period. The powers of the “centres of calculations” that make up the nodes of networks significant for the shaping of Modern society (science, civil institutions, and medical systems to name but a few) can be explained by the manner in which they mobilise inscriptions. As Latour ties these effects to the possibilities offered by the technology of the printing press, it is therefore interesting to investigate empirically the relation of new technologies, such as computers and electronic networks, to these effects. New technologies may reshape these, making some more significant, or less relevant.

Inscriptions are particular in that they make ‘mobilisation’ possible. The features that make inscriptions mobilisable are worth considering, since they provide a way of linking practices, institutions and cognitive claims. Inscriptions, Latour argues, are not in and of themselves explanatory, but become so when considered as mobilisable allies, in the sense that they can convince someone to take up a statement, to make it more of a fact or to change one’s behaviours. In the Latourian understanding of inscriptions, two main concepts stand out. First, the inscriptions are the result of scientific activity as well as the basis for further work. Modern medicine then, is the shift from “small scale practice to large scale manipulation”, so that:

the same medical mind will generate totally different knowledge if applied to the bellies, fevers, throats and skins of a few successive patients, or if applied to well kept records of hundreds of written bellies, fevers, throats and skins, all coded in the same way and all synoptically present (Latour, 1990).

This is the level of analysis where the efficacy argument is most potent, linking practices and achievements. It highlights how, for example, individual brain scans produced in a session can become increasingly significant (in all senses of the term) as they are “cascaded” with others, and once so assembled, can come to stand for a population. This set of cascaded representations accrues authority, so that it can in turn serve as a diagnostic tool, so that further individual scans will be made for comparison with this new standard. Alzheimer’s patients, or normal males or dyslexics could all be populations whose brains are averaged.

conservative bias may also make for a less sensitive approach to radically new possibilities arising in new contexts.

I take the term inscription to be very close to my own use of ‘representation’, though with a greater emphasis on the ‘writing’ process, and a focus in Latour’s discussions on inscriptions as the result of machines (Latour and Woolgar, 1986).

Latour cites Eisenstein (1979) at length.

Historians and some sociologists will be right (and quick!) to point out that “it is rarely the same medical mind”, highlighting the importance of historical contexts which also determine how a given mind will operate in making this argument.
A second main aspect of this theory of inscriptions is the semiotic nature of the circulation of inscriptions as "immutable mobiles." The term is paradoxical enough to point to the difficulties in its use: how can something be the same here and elsewhere, no matter where? This question need not be posed in extreme constructivist mode to leave the analyst perplexed. In that sense, a concept like Star's boundary objects, highly defined in local, individual use, and looser and more flexible in communal use, emphasises the need for more sensitivity to the contexts of inscriptions, while maintaining a focus on circulation (Star and Griesemer, 1989). Establishing communality or stability of meaning is work, an outcome, and not a given of modern inscriptions.23 This thesis is precisely an attempt at showing how the digitality of representations is given meaning as mapping practices develop, and how contexts are developed so that these representations do become mobile.

But even if inscriptions do not start out as immutable mobiles but rather sometimes end up that way, the features Latour identifies are useful as categories for an empirical analysis of a new, digital, kind of inscriptions. For example, the possibility of combining inscriptions is attributed to optical consistency. Yet, in the case of digitised imaging, it is not so much the straightforwardly geometric relationship of Renaissance perspectival drawing that determines the combinability of scans. With digital imaging, the

23 See Chapter 5 for an empirical demonstration of this. Heath for example, seems to tend in the direction I am indicating, as her analysis moves from the immutable mobile explanation to discussion of how she follows slides from the lab to the conferences and describes their functioning as "mutably mobile" as their meaning changes (Heath, 1998).
visual becomes quantitative, and traditional notions of perspective based on the observer are exploded (Kember, 1998). While inscriptions encompasses image, number and text, it may be necessary to distinguish these aspects of representations to understand the development of brain mapping, since the circulation of particular types of knowledge claims may be shaped by the form of this knowledge in relation to the ‘speciality’ dimension in medical research (Hiddinga, 1995), or more generally, to the epistemic style of a given scientific culture (Knorr-Cetina, 1999).

Such distinctions in modes of representation of knowledge have been shown to arise during the birth of Modern science (Stafford, 1991). Stafford has traced how a hierarchy of modes of representations developed and affected the way visual evidence, in particular, was considered. Because of a distrust of sensory perception, specifically associated with the visual, images were denigrated and largely abandoned in favour of quantitative and textual modes of representation. In one of her recent works, where she addresses more contemporary phenomena, the neurosciences are pointed out as a field where visual information is ‘inundating’. She has hailed a new era in this stream of research where visualism is gaining acceptance. Not content to observe this phenomenon, she has issued a call on those with an understanding of images, art historians, to grasp a (renewed) mandate to explain images, since ‘understanding their significance is enhanced by knowing that they still reverberate with allusions developed in the early modern.” She sees the cross-sections of PET scans as neo-Albertian windows on mental operations, and worries about the potential for insurers, employers and other institutions to exclude individuals on the basis of such representations (Stafford, 1996). While there is indeed a neo-Albertian element to the understanding of brain scans, I will show that it does not constitute the dominant understanding of brain scans. The point does remains that inscriptions must sometimes further be specified because of their associations with literary, quantitative or visual registers, and the relative valuation of these in Modern Western science.

Indeed, the ‘visual’ is also not a single entity to be translated monolithically into new media. A culturally specified set of practices warrants visual apprehension by the (medical) researcher. Lisa Cartwright draws a contrast between two ‘gazes’, two arrangements for seeing:

The qualitative and empirical gaze of eighteenth- and nineteenth century anatomico-clinical perception that Foucault describes overlapped with and was ultimately challenged by the relentlessly analytical and quantitative gaze demonstrated in the cases considered in this volume, a mode of perception carefully incubated within the laboratories of physiologists and medical scientists and finding its expression in an unlikely range of institutions and practices, including the hospital, the popular cinema film, the scientific experiments and the modernist art work (Cartwright, 1995).

The medical gaze has indeed especially been the subject of analysis, in relation to Foucauldian notions of medical surveillance and bio-power. But whether for medical or
scientific purposes, "the expert’s gaze [must] be ‘clarified in order that the disease should give up its hidden secrets into the domain of the visual (Marshall 1990)’ (Terry and Urja, 1995).”

To return to the discussion of Latour’s features, geometric perspective and optical consistency are also identified as key features of inscriptions. While indeed a dominant mode of representation, geometric perspective too is best problematized, in terms of the subject/object relations that this mode of representation implies. Albeit very significant, optical consistency is actually only one of many forms used to subvert realist claims in representations, as historians of science Lorraine Daston and Peter Galison (1992) have shown. While Latour replaces objectivity with ‘optical consistency’, I would argue that it is rather one form of visual objectivity. Objectivity is generally defined in contrast to subjectivity, and moreover, as the result of the removal of subjective influences (Daston, 1992). Using a range of atlases as a chronicle of changes in the concepts of objectivity, Daston and Galison show how the ideal of truth to nature can vary and be achieved by contrasting representational strategies. The representations featured in the atlases can be ideal, corresponding to the notion of what nature should be. The ideal representation is the product of aesthetic judgements so that the illustration can be free of accidents or idiosyncrasies. In turn, a characteristic member of a category might be chosen, and represented in minute detail. A third mode of objectivity arises in connection to the mechanical truth. Human subjectivity, unable to refrain from interpretation is to be bypassed, and the ‘constitutive and symbolic functions of the machine blur, for the machine seems at once means to and symbol of, mechanical objectivity (Daston and Galison, 1992).”

![Figure 5 A probabilistic brain atlas](http://www.loni.ucla.edu/~thompson/disease_atlases.html)
The data from subjects is superimposed, and will enable the evaluation of the probability of a point being located in a particular region (33%, 66%, 0%). Such an atlas might be population based (i.e. schizophrenic brains, etc).

Reproduced from [http://www.loni.ucla.edu/~thompson/disease_atlases.html](http://www.loni.ucla.edu/~thompson/disease_atlases.html), courtesy of Paul Thompson, UCLA Dept of Neurology
Daston and Galison also reflect on what has been the role of the atlas itself: "the purpose of the atlas was and is to standardise the observing subjects and observed objects of the discipline by eliminating idiosyncrasies—not only those of individual observers but also those of individual phenomena (Daston and Galison, 1992)." The probabilistic atlas of the brain (see Figure 5) further broadens the role of the paper atlas, since in its electronic form, it is an automated tool developed to quantify the idiosyncrasies found in particular brains. To borrow a phrase, the subjectivity of the brain is 'cancelled out by dividing by the subject' in the constitution of a digital atlas. The constitution of brain atlases, for example, relies on a particular version of what makes an inscription objective.

![Figure 6 The volumetric “canonical brain”, and the flattened cortex of the 2D brain.](Reproduced from the van Essen Lab homepage.)

Similarly, digital imaging and the tensions between the more common medical 2D scans and the new 3D world created for viewing the brain cannot be apprehended under the feature of flatness of Latour's inscriptions—though flatness hints at an important aspect of representations (see Figure 6). Debates about how best to represent the cortex as a 'volume', as an unfolded, flat, map versus an idealised, inflated sphere (not shown) are not interchangeable, but rather represent different disciplinary traditions and tools within the neurosciences.

Neither can the scale of images be changed at will without changes in their internal proportions—another property attributed to immutable mobiles. When brains are aligned into similar spaces for comparison, the transformations must sacrifice in some measure the 'true' relations to different parts of the brain, thereby confounding the proportions (See Figure 7). In the brain imaging community, this is the source of a debate that has sometimes taken surprising turns: a template of a Japanese brain is currently in
use, and Japanese researchers argue that it better maintains the proportions of the Japanese brain than the Western templates (Kanno et al, 1992). When approached empirically, Latour’s features of immutable mobiles therefore highlight significant points of debate in the developing representational practice that is brain mapping.

![Figure 7 Various aspects of one method for transforming brains to a standard space.](image)

The ICBM atlas transformations, which transform the brain to conform to a standard space.

Reproduced by permission from *Neuroinformatics*.

Therefore, the digitalisation of representations of the brain will be analysed, using Lynch’s ‘digitalism’ as a framework for understanding how a different order of work (ranging from the epistemological to representational) might arise in digital contexts, and Latour’s features of inscriptions as fruitful categories of empirical analysis.

### Dimensions of Representations

“A new visual culture redefines both what it is to see and what there is to see (Latour, 1990).”

Representations in brain mapping will therefore be used to trace how experimental practices showing brain and mind develop and how the uses of technologies change in relation to these new representations. Representational practices evolve as the result of processes; interdisciplinary collaborations, the growth of digital technologies, and the visual aspects of these investigations will be shown to have particular impact on the new objects and practices that arise from this new stream of research. I will also highlight the particular contexts in which these representations have become ubiquitous and the constitution of frameworks in which mind and brain can be translated into powerful representations. Ultimately, my goal is to contribute to an understanding of ongoing shifts in systems (of healthcare, justice and education) that have relied on a different parcellation of what is meant by labels such as mind and brain, although addressing these in detail is beyond the scope of the present project.

Each chapter focuses on a particular kind of representation and on the issues of scientific knowledge and practice it raises. These can be take to correspond to ‘scans’ and the need to develop ways for nature to speak through technology; ‘maps’ and the question
of method for mind-brain correlations; the ‘visual as empirical basis’ and discipline formation; ‘atlases’ and normative interventions. If there is a direction of representations in this thesis, it is a social and technical one, like the movement of an assembly line (Lynch and Woolgar, 1990). Indeed, encounters with ‘originals’—the ‘optical’, the ‘patient’ in the flesh, the ‘real work’ of scientists—also spring up in chapter 5. Each chapter is therefore not to be read as a move further ‘away’ from an original, but to more complex manipulations and translations.

The next two chapters will address shifts in the understanding of brain and mind through the development of scanning and mapping conventions. These chapters specifically take up the interactions between digitalisation and biologisation, looking at how scans become meaningful traces, and come to stand as maps of the mind-in-the-brain. Chapter 2 contains a discussion of the many strategies used by different researchers, in the course of the eighties, to establish what can be learned from scans, focusing on the biological and digital contexts of reference used to ground the data provided by PET. Chapter 3 shows how mapping becomes both an experimental strategy and an organising metaphor for discovering the mind in a new space. The next chapter focuses on the development of a hybrid epistemic culture particular to brain mappers; the result of the integration of quantitative and visuo-spatial approaches to the brain and mind, constituting a quantitative visual culture. Chapter 5 considers how representations developed in brain mapping are cascaded in particular ways, constituting a new kind of mutable mobile. This enables brain mapping to occupy an increasingly significant place in neuroscience and a new normativity to develop around scanning and mapping. The concluding chapter contains reflections on the new features of knowledge developing around brain mapping, and how these might compare to other projects where biologisation and digitalisation figure prominently. Finally, the thesis ends with reflections on how to pursue further analyses of digitalisation as a growing representational mode in science.
An introduction for cognitive and neuro-scientists

Those who will have read Knorr-Cetina’s latest work will be familiar with her notion of epistemic cultures. I was delighted to find an echo of this concept while reading Daniel Dennett’s *Consciousness Explained*, where he puts forth the notion of epistemic curiosity as an important feature for understanding the brain. I reproduce a passage where this notion is introduced, early in the book:

“the only work that the brain must do is whatever it takes to assuage epistemic hunger—to satisfy “curiosity” in all its forms. If the victim is passive or incurious about topic x, if the victim doesn’t seek answers to any questions about the topic x, then no material about topic x needs be prepared. (where it doesn’t itch, don’t scratch) ....”

I ask readers not familiar with science studies and constructivism to try to use this concept to understand what will follow. What is discovered is what is sought, and in the course of discovery, nature is part of the contingencies, but not a determinant one in and of itself. The rest of this thesis argues that a dynamic similar to that of epistemic curiosity operates at the level of scientific activities, and that my own endeavour to learn (about) these activities has given me insight into it. Because my own epistemic curiosity contrasts with that of brain mappers, it can serve to highlight theirs. Ideally, if mappers’ curiosity can in turn be stimulated by what my own epistemic curiosity has yielded, this forms the opportunity to communicate, and shape perhaps a different kind of epistemic hunger. I cannot dream of a better beginning to opening up what is considered the relevant context of brain mapping, as this thesis aims to do.
In a typical cognitive PET experiment, subjects are injected with a radioactive tracer ($H_2^{15}O$) while they are performing a cognitive task (e.g. reading words; recognising pictures). The PET scanner detects distribution of the tracer in the brain, which is an index of the distribution of cerebral blood flow, and hence, the pattern of brain activity. A standard experiment consists of 6-19 scans per subject, made 10-15 minutes apart. Each scan may represent an experimental condition, but to increase the signal to noise ratio in the blood-flow data, it is common to use multiple scans per subject and condition. To further increase the statistical power, the data from a number of subjects representing the same condition are usually averaged. Before averaging, the images from different subjects are transformed to a common brain space. This is done on the basis of brain landmarks inferred from the PET images or from the MRIs of the subjects with both methods giving similar results. The specific locations where differences are observed [activations or deactivations, in comparing the reference and the target tasks] are usually expressed as three-dimensional $(x, y, z)$ coordinates in reference to the stereotaxic brain atlas of Talairach and Tournoux (1988).²⁴

Brain mapping is said to have opened up the possibility of a new collaboration between the sciences of mind and the sciences of the brain. This collaboration, brain mappers claim, will yield a new kind of science and scientist:

“At no previous time in our scientific history have we been in a better position to achieve the crucial working relationship between the behavioural and brain sciences that Sherrington envisaged.....Success in this exciting endeavour is dependent on a close working relationship between cognitive scientists who understand how to characterise and study elements of human behaviour and neuroscientists who understand how to study brain function at a systems level....We can expect a new breed of scientist, whom we might call cognitive neuroscientists, to emerge from this partnership, equipped with the interdisciplinary skills necessary to be successful in this challenging area. (Raichle. 1994b).”

²⁴ From Roberto Cabeza and Lars Nyberg (1997), edited slightly for legibility by author.
It is precisely what makes up this “close working relationship” and its effects that will be investigated in chapters 2 and 3. The description of a typical experiment above contains a number of concepts that have been taken over from the experimental strategies of various disciplines and some that have been developed specifically for brain mapping. In this chapter, a key part of the working relationship will be shown to be constituted through the development of a digital space in which to measure mind and brain. This chapter will examine how, for example,

"Brain imaging offers psychiatry a broad range of investigative techniques that fulfil the popular fantasy of being able to ‘read the mind’ albeit in the form of ‘seeing the brain’ both structurally and functionally (Andreassen, 1988).”

By the end of this chapter, the significance of digitalisation for shaping how the mind came to be read by seeing the brain should be clear. Chapter 3 will address the aspects of mind which came to be read in this way.

New possibilities for collaboration between mind and brain sciences and for learning about the mind through exploration of the brain involve a number of changes and innovations in the way functional imaging is pursued and organised. New brain imaging technologies certainly play an important role in this process, though some brain mappers have decried the fact that too many of the new collaborations have been attributed to new scanning possibilities:

“Although continued technical developments attract the lion’s share of attention, of far greater importance for the maturation of the field is the expanded participation by scientists in adjoining, complimentary disciplines. …Human brain mapping is an emerging discipline (Fox, 1993).”

This chapter will consider the changing participation of various clinicians and scientists, and will show how closely this is linked, not only to the development of scanners, but also to the development of a set of representational conventions embedded in digital technologies. I suggest in this chapter that conventions can be viewed as a boundary object, part of the shared tools that “specify the content of professional agreement and are privileged sites of inter-professional debates (Loewy, 1992).” As with any other new technology, correlation between measures and a meaningful context must also be established; in a context of clinical care, measures have to make sense in terms of concepts of disease (Amsterdamska, 1998). This is also true in research settings, where measures have to make sense in terms of phenomena, which disciplines take to be their object.

The development of meaningful ‘scans’, providing important information to both brain and mind scientists, is not solely the result of having “a window on the brain”, opened up by scanners, but of continuous efforts to build, frame and learn to look through it. The development of particular contexts in which new types of information can be meaningful has been told before (Pasveer, 1992; Yoxen, 1987) and will serve as
important theoretical models here. Representations will then be taken as point of entry into the practices and agreed-upon conventions on which the knowledge claims of scientists are made since “for such images to be relied on as evidence, there must be general agreement as to their value and reliability, and there must exist a set of procedures for generating them (Yoxen, 1987).” In developing new uses, for ultrasound, in this case:

“Different groups pursued different strategies and explored the utility of different graphic conventions, even though a common aim was improved diagnosis. What seemed an acceptable engineering solution was somewhat variable, although in each case the basic challenge to be faced was the validation of the resulting image through some sort of visual comparison. (Yoxen, 1987).”

Yoxen notes that a common way of making sense, namely visual comparison, can be observed in the various strategies applied to ultrasound results. The development of x-rays also involved comparative recovery and reworking of diagnostic criteria in x-ray images. Comparisons in this case were made with anatomy, to other diagnostic results, and between x-rays, so that

“x-ray workers make this ‘world of the unseen’ into a visible world by actively searching for means of comparing the unknown shadows to known representations of the body….The unknown shadows were made to fit other, stable, well-known diagnostic practices… (Pasveer, 1992).”

Pasveer goes on to show that if x-rays open a window on the world, it is a remade world. Clearly, there is much work involved in establishing the meaning of new kinds of information, and this usually done using a number of strategies, which may have a common element, for example, visual comparison or relevance to diagnostic categories.

In terms of PET scans, the development of meaningful uses of these scans is characterised by two features. First, its development straddles not only a number of applications and research questions, but also two modes of representation, the optical and the digital. As such, this case highlights the kinds of changes that the increasing use of computerised imaging, data processing and modelling may bring about, such as quantitation and the use of statistics, and automation and manipulation. Second, as an evolving framework for understanding PET scans, digitalisation supports conventions which standardises some aspects of the work while also allowing for increased inter-disciplinary collaborations around PET, and eventually, even with other functional imaging technologies. This chapter will examine how conventions for understanding PET scans change as new groups become involved in the use of scanners and as they try to pose research questions in which their ‘own object’ (pathology, cognition, etc) can be apprehended in the scans. By developing a framework that could accommodate a number of meaningful measures, functional imaging data came to be significant in an inter-disciplinary context. I will argue here that as conventions developed, they enabled PET scans to be used, and shared meaningfully between disciplines of mind and brain, and
were an important component in establishing PET and brain mapping as interdisciplinary endeavours.

**Anatomy: The mother of all neuro-disciplines**

The complexity and centrality of PET to brain mapping, already described in the first chapter, means that a number of points of departure can be chosen for telling the story of its development. As a technology, and a generously state-sponsored one, PET developed in parallel to work on nuclear reactors and accelerators. As a fairly exclusive tool, it was only available in a handful of academic hospitals, located close to centres for physics research, where work was done on the potential clinical uses of the scanners in nuclear medicine. Arguably, this early clinical context tied the production of scans to diagnostic or therapeutic intervention, of which anatomy was an important component. In the study of the brain too, anchoring functional data to (anatomical) structural information is still seen as a major stepping stone for using PET. Neuroanatomy is considered the "mother discipline" (Senior researcher, trained as physicist), "the organising structure for information about the brain (Pechura and Martin, 1991), and "the most fundamental language of communication in neuroscience (Frackowiak et al, 1997).

But how PET scans were to be related to anatomy was not clear for researchers and clinicians in the early eighties. The tension between PET as a tool providing information about physiology and anatomical knowledge is a central theme to the history of how PET scans became meaningful. Reflecting on the development of PET, around 1994, sociologist Anguelov observes that

---

25 Like many other applications around 'radioactivity', this research has ties to the military-sponsored research of the war and post-war period. Isotopes became available as a by-product of the development of nuclear reactors. They were offered for scientific research by the American Atomic Energy Commission in the *Journal of Science*, in 1946 (Kevles, 1997). These were used for the destruction of tumours (not imaging) at that time, and the medical spin-off of nuclear research became an integral part of the 'atoms for peace program' of the 50s, under Eisenhower (Kevles, 1997). This connection was also to be found in other countries than the United States—European countries where atomic centres were built also supported this type of research, so that the locations of early PET centres map closely unto those of atomic research centres. Witness this map of PET at the following site: [http://www.epuh.org.br/cm.001/pet/pet_hist.htm](http://www.epuh.org.br/cm.001/pet/pet_hist.htm). A possible exception, the centre in Montreal, turns out to have its origins in the work done at Brookhaven. Yamamoto, one of the pioneers of PET imaging in Montreal, developed a circular array unit around 1966, and took it with him when he went to work in Montreal (Anguelov, 1994).

26 While it is difficult to argue that PET has not been successful clinically, there does seem to have been a rather protracted development period, perhaps especially in comparison with (medical) other scanners. 'Clinical PET' for example has been repeatedly announced for the past two decades, but found slow to emerge (Karp and Freifelder, 1992; Lumsdon, 1992). Accusations that PET was not living up its promises were heard in the late eighties from academic neurological, psychiatric and neurosurgical corners (Rapoport, 1991). Well into the nineties, PET was still said to be "waiting in the wings" for use in patient trials (Sawle, 1995). State sponsorship, which arguably prevented market development, has been blamed for this (Kevles, 1997) as well as reluctance by insurance companies to reimburse scans. and regulation problems (Gershon, 1995). Others have argued that PET was held back, because undergoing closer scrutiny, in reaction to feelings that its predecessor, MRI, was not properly evaluated before being brought widely into use (Coleman, 1993).
“PET is only in rare cases used alone, since it is not the function per se that is of interest to scientists and clinicians, but the localisation of the function in the brain. Therefore, PET images (which visualise a function of interest, FOI) are coupled with MRI images (which visualise a ROI [region of interest]). This coupling requires more refined approaches to the very scanning of subjects and convenient algorithms to archive an anatomo-physiological match that is idiosyncratic for each subject... (Anguelov, 1994)

Anguelov suggests that the coupling is part of the “thinking of PET people”, and also furthered by the presence of MRI and CT scanners where PET scanners are also found:

Thus in every respect PET is something that comes after or is built upon the preceding imaging techniques. In this sense, in BI [brain imaging] MRI serves as the referent to PET. The underlying reason, I propose, resides in the fact that biological structure and function are not only the two sides of a coin, but they exist in a mixed form in the thinking of PET people. The exciting feature of PET is that it ‘shows’ function but nobody contends that this ‘show’ has a meaning without being correlated, matched or referred to the anatomical picture of the same region, section, volume, etc. (Anguelov, 1994).”

Anatomy does indeed constitute a central theme in the use of PET, and the coupling of structure and function are deeply ingrained in the current use of PET. But what is meant by anatomy is not self-evident and how a relationship between types of data and various technologies is achieved has varied over time. To problematize this further, I will show that correlation and matching are highly complex, and that the relation of structure and function gradually changed, as who counts as “PET people”, their tools and goals also changed. I will therefore analyse how anatomy, as a key ‘context’ for using and understanding PET scans, is formulated and sometimes contested in multiple ways, and depends on the uses to which PET is put.

In the early eighties, anatomy was important but problematic; some of the explicit discussions of the need for a meaningful content of these scans insisted on the importance of anatomy for understanding the brain. In an editorial, John Mazziotta, a neurologist by training, stated that traditionally,

“neuroanatomy has provided a common language of communication among investigators” but that “present-day techniques that employ tracer kinetic approaches to image the three-dimensional cerebral distribution of physiological...”

---

27 One strand of this story will not be included in subsequent discussions, but deserves to be noted here. At the point where the method to trace blood flow (H_2^18O method) developed, a greater distinction grew between ligand studies and blood flow studies. In the former, the notion of PET as a molecular technology has developed, coupled to rigorous, absolute quantitation (Jones, 1996) and sometimes aligned to the powerful bio-medical research areas of molecular biology (Wagner, 1992).
and biochemical processes provide challenging new problems to this old discipline (Mazziotta, 1984)."

This editorial in the *Journal of Cerebral Blood Flow and Metabolism* was in effect a call to improve the use of new techniques, because

"the exchange of information, the credibility of results, and the power of these techniques will in part be determined by our ability to find standardised, reproducible and accurate methods of analysing data from these sources (Mazziotta, 1984)."

The issue of the meaning of scans is posed here in terms of the challenge and need to reconcile this new data with anatomy. Subordinate to this agenda are other issues, including the need to find a way to handle 3-D data, to perform studies across many subjects and to construct a model of cerebral function. This editorial also contained an announcement of a series of workshops to address these issues, organised by Mazziotta and Stephen Koslow, of the National Institute of Mental Health.

The main strategy eventually adopted to achieve these ends was the spread and development of the Talairach system. This system mentioned in the first chapter has indeed become a marker of brain mapping work. But this convention does not only unify members within the mapping community, it also sets it apart from the larger neuroscientific community:

"Newcomers to the field of functional neuroimaging, particularly those reading the PET activation literature for the first time, are often bewildered by the abandonment of traditional neuro-anatomic nomenclature in favour of a set of coordinates (Woods, 1996)."

---

28 The cumbersome description of what these new techniques measure in this quotation is of course not independent of the ongoing search for what is shown by these technologies.

Two controversies flared up, in the mid-eighties and mid-nineties, challenging what the imaging technologies were "really" measuring (Barinaga, 1997). Blood flow is coupled to neural activity, but the exact relation is not considered to be clearly understood, though recent developments have focused what the relationship might be (Magistretti et al., 1999). The neurobiological basis of the blood flow and neuronal activity coupling is still not understood (Raichle, 1996b; Friston, 1997).

29 Digital 3D imaging permeates our visual culture to such an extent that there is a danger of forgetting how novel a mode of representation it was up until a few short years ago. As this chapter demonstrates, the constitution of conventions for using and making sense of data in this form has been anything but linear, and full of contingencies, accidents, and unintended consequences.

30 The involvement of the NIMH here, and throughout the next decade, should be understood against the background of the Institute’s conscious decision to move away from its public health profile and take a turn to lab-based, biological investigation, and a focus on a neuroscience program. From early eighties, the NIMH was therefore committed to more “empirical” work, and reorganized its research activities around diseases, forming alliance with patient groups. The Decade of the Brain was a further opportunity to move in this direction. In the nineties, the ‘parity’ of mental illness with other diseases (meaning both destigmatization and better health insurance coverage) became an aim of the NIMH. Finding biological causes to mental illness was considered to buttress this aim. After its separation from the NIH in the sixties, the NIMH became more “social”, its return to the NIH marks a turn to the “scientific”. 

31
PET has been reconciled to the mother discipline, but not on traditional terms: shifting away from neuroanatomy through digitalisation involves leaving the optical framework and linguistic labelling of traditional anatomy. I will argue here that the ‘abandonment’ of nomenclature has been the result of a series of development of the community, including the involvement of new groups of researchers in functional imaging, eventually also leading to transformations of the Talairach conventions themselves. By tracing the adoption, transformation and debates around various applications of ‘anatomy’ the establishment of a meaningful context for scans, the constitution of this new stream of research and the establishment of collaborations for mapping the mind in the brain can be analysed.

**Metabolic Landscapes**

In the early eighties, PET scans were evolving in a number of nuclear medicine and medical physics contexts, where they were used to make physiological measurement of brain metabolism (glucose) and blood flow.\(^1\) Scans were used to measure “local cerebral metabolic rates”, in the tradition of physiological and metabolic studies of the brain (Kennedy, 1991). Much of this work had previously been performed on animals, and in humans to study epilepsy and stroke—conditions defined in terms of a physiological abnormality. These and other clinical conditions (Huntington’s, Parkinson’s, dementia) were explored with PET in humans. While many studies examined ‘states’ of the brain, some work done in ‘normals’ measuring activations, to determine resting state (Mazziotta et al, 1981a). Visual and auditory stimulation were investigated (Mazziotta et al, 1981b; 1982), as well as more purely ‘mental’ activity such as visuo-spatial imagery and memory (Roland, 1985). Besides serving to explore function in the human brain, these studies were also justified in clinical terms. For example, scanning the brain, while the subject was receiving visual or auditory stimulation, could form a basis for developing ‘activations paradigms’. Using these, neurologists might highlight slight dysfunctions in the brains of epileptic patients, that would not show up in the brain at rest (Mazziotta and Engel, 1984).

In order to properly understand these scans, three requirements were mentioned: there is the need to have knowledge of models\(^2\), scanner technology and of “neuroanatomic relationships of sizes and orientations” (Mazziotta, 1981a). Specifically, knowledge of anatomy is necessary because of the spatial resolution of the scanner, and because of need to understand ‘size effect’. This is a complex problem, but basically, it refers to the fact that small structures will not appear as distinct from larger ones, unless they have a very high concentration of radioactivity. What is significant about the mention of this problem for this chapter is that it indicates that anatomy must be taken into account to understand the detected physiological data. Another problem identified in

---

\(^1\) Other clinical applications were being developed in oncology and cardiology during this time but will not be discussed here. Sawle (1995) provides a review.

\(^2\) This refers to the many models used in PET technology, among others the need for models of the behaviour of radioactive tracers and their rate of decay.
these early studies is that voxels\textsuperscript{33}, the spatial unit in which the scanner makes measurements, can overlap a number of structures in the brain.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{digital_grid.png}
\caption{Digital Grid}
\end{figure}

This can be thought of as a grid being laid onto the brain, and within one 'square', there may be more than one structure. The value of a square is therefore made up of the combined values of the structures that fall in the square. The smaller the square, the less likely it becomes that many structures will fall within one square. Having more squares, however, may not always be possible because of the size of detectors, for example, or because of the computer power needed to process more and more 'squares'. Note that the above is a 2-d representation of these issues—the data is actually in three dimensions, so that the squares are 'actually' cubes.


\textsuperscript{33}Voxels, a neologism derived from the slightly older pixel (picture element), describes a 'cubic' unit of digital data.
The resolution improves, bringing scans closer to an anatomical depiction, but investigators still seek ways to control the scanner's sampling beyond its resolution.

Reproduced from http://www.epub.org.br/cm/m01/pet/pet_hist.htm

The significance of this concern is that the digital space of the scanner must also be related to the anatomy of the brain. The interaction between physiology and anatomy, and between scanner 'sampling grid' and anatomy, are therefore to be taken into account in order for scans to be interpreted. There was no consensus among PET investigators on this issue, and some mixed the various approaches listed below.

One strategy for understanding PET scans was to minimise concern for the scanner's sampling and anatomy and to consider scan as physiological or metabolic landscapes. This meant reading scans 'internally', for example, by assuming symmetry and looking for asymmetries which might be typical of a condition. Here, the grid was ignored, and scans were analysed as (optical) images meaningful to an observer.

PET could also be applied to clinical issues being tackled by structural imaging. Some neurologists tried to subordinate anatomy and show the superiority of PET in detecting pathology or brain abnormalities. This rationale for the use of PET was based on the assumption that metabolic change might indicate changing physiology, and that such changes precede anatomical changes detectable by structural imaging technologies. A number of articles appeared in the early eighties, comparing the scans in clinical cases and emphasising the differences between the two types of scans. CT scans are compared to PET, and where no abnormality is visible on the structural scan, the PET scan is shown to indicate abnormalities in cases of blindness (Phelps et al, 1981), epilepsy (Mazziotta and Engel, 1984) or aphasia (Metter et al, 1981). The suggestion made is that the functional definition of these conditions might be useful clinically, because it can provide 'deeper' or earlier indications of pathology, before structural change has taken place.

*34 This strategy was also used in the early development of other imaging technologies, such as thermography (Blume, 1992) early chest x-rays (Pasveer, 1992) and positron emission mammography (fieldnotes).
Anatomy was an important element in interpreting these scans, if only because of the assumption that anatomy could be read through PET scans, in order to identify the structures of increased or decreased metabolism.

But if anatomy was an important element to correlate with PET data, there was also an effort to explicitly distinguish PET scans from anatomical ones. The importance of anatomy for using and understanding the new scanners and the results they produce can also be seen in Mazziotta’s editorial, which reflected on the state of metabolic imaging at the time. Neuroanatomy is to be challenged by these new metabolic scanners, in the sense that the space of functional cerebral processes cannot be subsumed to an anatomical understanding:

“A basic premise that must be discarded is that structural and functional anatomy are equivalent. Although one can and should seek to find concordance between structural and functional anatomy, analysis schemes that rely on assumed equivalence will be biased (Mazziotta, 1984).”

This editorial marks the beginning of efforts to standardise the analysis of PET, and especially to develop a concordance between the two types of data and to reference PET to anatomical information. The need to have a ‘baseline’, independent but related to the physiological PET scans was a recurring suggestion: “Regional analysis of a physiological measurement” was to be related to the corresponding anatomical structure of areas in the PET image. Fox and colleagues agreed with Mazziotta about the need for

“a method for determining anatomical location within physiological brain images that is itself independent of the physiological image [to] be developed, standardised and accepted into general use (Fox, et al, 1984a).”

Therefore, a number of avenues were opened in order to establish PET’s identity as a technology and its particular contributions to the study of the brain. The tension between physiology and anatomy has been and remains quite important for understanding the development of PET. In this early period, there were attempts to establish PET’s superiority as an earlier marker of (pathological) change in the brain, and repeated insistence that it could not and should not be reduced to an anatomical scanner—by distinguishing PET from the anatomical understanding of radiologists and their scanners, the distinct identity of PET as a nuclear medicine tool could be maintained. Yet, the drive to make PET clinically relevant involved the recurring call to find a proper “concordance” between the two types of data.

The message for a need to distinguish between these two types of data has often been repeated in the next decade, as technical improvements to PET brought its resolution closer to other imaging techniques, such as MRI. While improving resolution makes the comparison of structure and function more probable.
"[a]s has been previously stated (Mazziotta 1984; Mazziotta and Koslow, 1987) functional and structural anatomy are fundamentally different entities. In reality, these images represent functional data that are not equivalent to structural information (Mazziotta et al., 1991)."

The clinical context of these developments and the growing presence of other (structural) scanning technologies were important in framing the tension between these “entities”. Imaging, at this time, had clearly captured everyone’s imagination (Raichle, 1996a). Researchers contrasted PET with other imaging technologies that were entering biomedical imaging spheres at the time, the x-ray CT and nuclear magnetic resonance scanners as they were then known. Even the way of naming PET pointed to spatial knowledge and structural imaging technologies. Mazziotta wrote about the PCT (positron computerised tomography) and in 1978, Feindel and Yamamoto had used the term “Physiological tomography” at the First Symposium on PET. At a time when other ‘high tech’ imaging technologies were being applied to the study of the structure of the brain (Blume, 1992; Kevles, 1997), PET was considered to be unique, in providing metabolic information. But while clinicians were enthusiastic about the CT and MRI scanners (Raichle, 1996a), no clear clinical application existed for the kind of information PET had to offer—about blood flow, blood volume, oxygen consumption, receptor pharmacology (Raichle, 1996a). In assessing clinical usefulness, the argument was often made that this technique provided information that had not been available with any other means, so that it could not be compared directly with any single other diagnostic tests (Powers et al., 1991). The uniqueness of PET was also noted in technology assessment articles (Volkow and Tancredi, 1986). But the uniqueness, potential and innovative character of PET were posed in terms of anatomy and anatomical diagnostic practices based on structural information. Given this medical setting and technological environment, anatomy was therefore to be the touchstone for establishing the usefulness of scans. The relation between the structural and physiological versions of anatomy was established explicitly using a number of technical strategies for correlation, that will be described in the next section.

**Landmarks: Physical Concordance as Principle**

If looking at PET scans was not considered an acceptable way of gathering information that would be relevant to clinically-defined conditions, the meaningfulness of scans could be improved through the use of landmarks. These would discipline observer and data, and enable matching physiological and anatomical scans, as though superimposing two versions of a landscape by virtue of matching landmarks.

---

35 I have encountered two explanations for the change of name, from nuclear magnetic resonance to magnetic resonance imaging. In the course of my fieldwork, researchers remarked that the term nuclear was dropped out of regard for public sensibilities, while Kevles (1997) notes that the term was changed in order to distinguish radiologists and physicians in nuclear medicine.
One early method for establishing anatomical correlation of PET scans was to match the scans to corresponding planes from anatomical atlases. Using this approach, the head of the subject or patient was aligned to obtain pre-selected slices, and these were then juxtaposed to anatomical representations.

Figure 10  Visual comparison of paper atlas and brain scan

This is the scan as 'landscape', where two representations, an anatomical and a functional version of the space inside the brain are to be evaluated optically and compared in the viewer's mind. Elements of this and following figures (scans) are reproduced courtesy of the Brain Imaging Centre (BIC), Montreal Neurological Institute.

Then boxes, representing 'regions', were drawn on the anatomical images and on the corresponding slices of the PET scan. Researchers would analyse the PET scan in terms of one or more atlas representation and measure how much activity there was in the regions selected. The Talairach atlas was used in this context, as one reference atlas among others. These were either paper atlases (Mazziotta, 1981a,b) or 'computerised' (Bohm, 1983), resembling paper atlases, but then in a digital format on a screen. The idea was to superimpose or juxtapose the two types of data.

This method was criticised as subjective, because the identification of regions was both highly dependent on the judgement of the researcher, and on the correspondence of the planes in the atlas and those in the PET scan (i.e. whether they were showing the same 'slices' of the brain). Many of the early PET studies from this period gave contradictory evidence and this was often attributed to problems in 'regionalisation', attributing an anatomical identity to a given region in a scan. Some PET researchers spoke of the need to establish the 'credibility' of PET in the face of these diverging results. In interviews,
some respondents talked about the work done during this period as neuro-impressionism—referring to the fact that the scans as ‘pictures’ rather than as ‘data’ were the focus.

**Head Holders**

Another approach consisted in making both structural and functional scans of subjects and patients, using elaborate physical means to ‘mark’ the spaces and therefore be able to compare them. This was done by using head holders which would establish the relationship of the brain of the subject to the scanner space. With the planes matched, anatomical information from an atlas or from a subject’s CT scan could be related to the PET scan. Collaborations with radiologists were significant for developing the use of head holders. These were based on systems developed to establish stereotaxic frames for comparing different imaging technologies, within the same patient (Greitz et al, 1980). The alignment of various types of scanners with the space of individual patients’ brains was used in the treatment of brain tumours by radiation treatment (aligning the scans showing the tumour with the radiation delivery apparatus), or for pre-surgical evaluation of patients, where correlated information from different sources was used in planning and performing neuro-surgery.

The underlying principle unifying these various practices for correlation was the linking of measurements and physical interventions (irradiation or surgery)—the alignment of scans and the ‘real’ space of the patient’s head for clinical purposes. But the use of head holders could be extended for brain mapping research, insofar as it would allow the combination of various types of data:

“Of special interest is the potential of combined information gained from transmission and emission tomography. The highly defined anatomical data obtained at transmission computed tomography may be used to select areas, or volumes, of interest in investigations of brain functions using positron emission tomography. This will allow a detailed mapping of human brain functions of hitherto unknown precision (Greitz et al 1980).”
Figure 11 Head holders for marking the space of scans in the early eighties.

Here, the brain scans are understood as landscapes, but landmarks are to appear in all scans (the metal frame positioned around the head) and are to guide the correlation of the various types of scans.

Reproduced from Greitz et al, 1980.

This method was taken over from existing clinical applications, where correspondence between diagnostic information and therapeutic interventions had to be established. The method was therefore originally aimed at correlating information for a single patient, in order to identify the particular pathology and interventions for that particular (abnormal) brain. Less restrictive head holders were also developed, involving padding, various materials that could be heated and moulded to the head and face. Pragmatically, making an extra scan involved the possibility of movement of the subject, unless very restrictive holders were used (and these were not very acceptable to normal subjects). Having to use another scanner was sometimes objected to as cumbersome. But more fundamentally to researchers, in terms of making PET data meaningful, while these head holders provided immobilisation of the head and enabled correlating information from different technologies in a single patient, they did not entirely solve the issue of relating the brain and the space of the scanner (the ‘grid’ problem), of comparing different brains to each other, or insuring that different ‘slices’ could be compared.

Templates

A third strategy, involved superimposing a template onto the PET image, so that an anatomical image of the brain could be individually adjusted (Bohm, 1983; Evans,
This involved matching the template to the individual subjects' MRI, and then applying the opposite transformations, to match the PET image to the template. The advantage of this method was that the templates used were labelled, and based on anatomical atlases, which provided some standardisation. This strategy also involved head holders, to match planes obtained in MRI and PET scans. The template was edited to match that particular brain (including asymmetries or pathologies in that particular brain) (Evans et al. 1988). The possibility of manually editing the template was especially important for a clinical agenda, since it made it possible to apply to patients, whose anatomy could not be assumed to be normal. For them, paper or computerised atlases which were based on normal anatomy could not provide a proper anatomical baseline. It also enabled researchers to identify fairly specific structures, which were important for answering questions of interest to neurologists, about the level of function of certain specific structures in the brain.

This method required a high level of expertise and neuro-anatomical knowledge for visual and manual, interactive fitting of the template to the MRI. It was also criticised as not fully objective, because not automated. The observer, possessing a refined skill of reading landscapes and matching landmarks seemed to offer and advantage in a clinical context but was of questionable value to those seeking standardisation and for whom pathology was not a prime concern. The authors of the method responded to the criticism of lack of automation in relation to objectivity:

"we sacrificed some objectivity by requiring the investigator to match the template to the MRI image and to manually adjust individual regions of interest as necessary to obtain a satisfactory match... but [this approach...] does allow for greater flexibility in dealing with pathological tissue (Evans et al, 1988)."

They also qualified what objectivity might mean in a clinical setting:

"The methods described here seek to take advantage of the pattern-recognition qualities of the human eye with noisy, low contrast anatomical images while

---

6 In this case, the authors mention that since the atlas was to be fitted to each subject, there was no need to gather data from a large number of subjects. A 'nice brain' was simply picked for the template, then adjusted for each subject. The 'nice brain' is part of a pragmatic strategy in functional imaging work used especially when pursuing validations of algorithms to identify structures automatically. Picking a 'nice brain' from a sample is a logical starting point, though researchers are quick to add that they, of course, consider a variety of brain morphologies in their validation exercises. Brains can also be excluded form a sample if they are found to differ too much from the norm. For a further descriptions of typical, representative and average brains seen chapter 5.

7 Researchers justify their work by insisting on completeness: "in defining the underlying gyral organization, the classification scheme incorporated as far as possible the gyral segmentation common to all of the above atlases (Evans et al, 1988)."

8 I will further analyse how attempts are made to reconfigure the clinical gaze into a digitally-supported one through tools for 'database diagnosis'.

9 Note how the human eye is described as an apparatus, a machinery for detecting that can be aligned with the technology of scanners and mechanical objectivity.
adhering to a predefined framework for anatomical mapping. The extent to which investigator bias will affect the results is a matter of some concern. However, as pointed out by Clark..., objectivity should be considered as the correctness and reproducibility of a method, regardless of whether human decision-making is involved or not. Rigidity of analysis that does not allow for patient variation is not a satisfactory form of objectivity (Evans et al, 1988)."

In order to make scans meaningful, a relationship to anatomy was therefore deemed essential in this period of PET development, where clinical goals were predominant. PET users therefore tried to both maintain the special insight provided by PET scans in showing metabolic information, while also trying to establish a concordance to anatomical information which they felt would enable a better evaluation and use of PET scans. Within the generally agreed-upon notion that anatomical information had to be brought to bear on the understanding of PET scans, a number of strategies were therefore proposed, each offering a correlation between anatomy and physiology, but with varying definitions and emphasis of what this relationship should be.

On the one hand, the need to correlate different types of information could be done taking the individual brain as integrating principle. When taking a subject or patient-centred, case by case approach, head holders could be useful. When this matching was done with a fiducial marker, a physical trace that would appear in both scans and enable a matching of the spaces, this resulted in the possibility of integrating data within a subject. This also enabled a fairly detailed and accurate correlation of structures of interest and the physiological measurements made in these structures. For clinical researchers investigating specific diseases, such as Huntington' disease where particular structures were already identified with the disease, PET could add a layer of information to the knowledge they already had in terms of that structure. Hence, PET added to anatomically-based knowledge. Unlike other technologies which became closely linked to particular diseases, like tuberculosis and x-ray (Pasveer, 1989) or epilepsy and EEG (Gloor, 1994), no such diseases were closely associated with the use of PET.\textsuperscript{40} PET studies seemed rather to be used as one approach among others in clinical research. On the other hand, there was also a desire to establish a standardised and objective approach to analysis, where results would be comparable between labs and studies, enabling research-oriented endeavours to grow. So while integration in terms of single subjects might be useful in clinical terms, it did not meet the needs of researchers trying to establish commonalities and differences across subjects to establish diagnostic norms, or to develop standards for PET as a new form of measurement.

One of the ways in which these contrast in agendas was becoming clear was in the notion of normal and abnormal anatomy. The possibility of dealing with pathological

\textsuperscript{40} Clinical indications for PET are also highly specific, and if calling them marginal is perhaps too strong, the use of PET could be typified as "second order". It is sometimes used for differential diagnosis (dementia/Alzheimer's, schizophrenia) or to establish 'viability' (of transplanted fetal tissue), progress of tumours after treatment, or for the localization of epileptic centres in pre-surgical planning.
tissue brains was important for clinical applications of PET. But the need for objectivity, in the sense of automation and standardisation, was still an important goal for the development of PET as a research tool, and pathological brains were considered to be antithetical to a normal and normalizable brain. The strategy of integrating information from different technologies in a single patient or subject was also more in line with clinical goals than research objectives, where generalisations across cases were desirable.

**Standard Anatomy: From Matching to Translation**

Another approach to correlation between PET and anatomy emphasised standardisation in the use of anatomy, so that there might be a stable baseline for the interpretation and analysis of PET. Fox et al (1984b) took as starting point the significance of anatomy in defining regions of interest (ROI) in PET analysis:

"Regional analysis of a physiological measurement has meaning only when the anatomical structure that corresponds to each area within the tomographic image is known (Fox et al. 1984b)."

But, according to these researchers at the University of Washington, St Louis, where much pioneering PET work had been done, approaches that matched 'planes' and anatomical atlases were neither sufficiently objective nor standardised enough (Fox, et al 1985). Using head holders, there was the possibility of movement, between scans. As well, they argued, the brain is known to vary between individuals, so that on given planes, different structures will show up in different brains (i.e. the same structures will not necessarily show up on the same 'slice'). For localisation in the cortex, the divisions considered important do not appear on MRIs which show only gross anatomical demarcations (Fox et al, 1985). Therefore, with the goal of standardising the anatomical referencing of PET scans and avoiding the need for the use of a second kind of scans, Fox and colleagues suggested a different use of atlases in relation to PET scans. Rather than superimposing structural and functional scans, either on a computer screen or in the mind’s eye, this group suggested that one space should be translated into the other, and that a given atlas, the 'Talairach' 41, should stand as the anatomical baseline for interpreting PET scans. 'Anatomy' was to be a chosen atlas, not a given patient’s or subject’s scan.

---

41 A further description of Talairach can be found in chapter 5, page 142.

The argument in the rest of the chapter shows the gradual remaking of this tool, so that in this chapter I will use the terms atlas to designate the original paper publication, space to refer to the use of Cartesian coordinate space and methods for transformation between the parts of the atlas (nomenclature, locations, anatomical referent), and system to refer to the complex set of companion techniques and tools developed most recently.
Figure 12 Translation of PET space into Talairach anatomical coordinates.

With Fox's proposal, the relation of pixels or voxels, the space of measurement of the scanner as shown conceptually in the figure of the 'digital grid', and the space of the brain could be made equivalent.
Figure 13 Interface of an automated tool for the translation of PET into Talairach anatomy

On the right are brain scans, transformed (and not simply visually compared) to Talairach space, and on the left are plates of the Talairach atlas, labelled and cross-referenced to anatomical names. This image represents a later, more automated application of the principles proposed by Fox in 1989.

The method was presented as the formalisation of a match of two similar coordinate spaces, that of the Talairach space and that of the scanner (tomograph). Describing the scanner:

"Each slice of a tomographic image is composed of regional elements (pixels) of uniform size and shape that are recorded and displayed as a two-dimensional rectilinear array."

The atlas of Talairach was also built using a similar space, argued Fox et al:

"Similarly, a three-dimensional coordinate system has been identified for human brain anatomy for use in performing stereotactictic neurological surgery (Fox et al 1985)."

Given these similarities,

"the brain, therefore, can be defined by two independent coordinate systems: that of the tomograph and that of the stereotactictic atlas (Fox et al, 1985)"
This marks an interesting shift in the conception of space in terms of scanners and
the brain. The method called on conventions about Cartesian space and translated the
space of PET scans in which function was represented, into the Cartesian space of the
anatomical Talairach atlas. The Talairach atlas contained some indications as to how
brains of different sizes and shapes could be transformed into a standard space, and the
Washington University group developed a computer program to effect these
transformations, after initial paper, pencil and ruler applications (Fox, int). Rather than
treating the brain and the scans as regions to be identified and related, as two versions of a
landscape (seen though anatomical and physiological lenses), this approach treated scan
and brain as grids, as sets of coordinate spaces. Rather than hoping for an optical
correlation by an observer (whose reliability was open to criticism), based on landmarks
or appearances, the grids could be reconciled digitally, enabling automation and the
guarantee of mechanical objectivity. This conceptual shift, from landscape to grid, and
the accompanying practices (slightly new ways of scanning) and new tools (software and
hardware to perform the calculations to match these grids) constitute an investment in the
possibilities of digital tools to a greater extent than methods relying on physical markers
for comparison.

In a digital space, the ‘original’ representation is not particularly valuable, and not
necessarily powerful because original. The value of digital representations resides in the
accuracy of algorithms, the usefulness of translations and manipulations it makes
possible. This method provided the possibility of aligning scans, and therefore allowing
for correction of movement of subjects during scans. While the amount of movement that
can be corrected is limited (and more problematic for fMRI than PET), movements of a
few millimetres do not matter as much if digital manipulations can correct for those
movements. This method was still somewhat of a hybrid, involving aspects of both
digital and optical approaches; an x-ray of the skull needed to be made, in order to
establish where to put the origin of the coordinates (point 0, 0, 0). This step was
eventually eliminated, in favour of more fully digitised and automated methods. In 1989,
a paper suggesting that the landmarks for fitting Talairach atlas to a PET scan could be
established without recourse to other anatomical scans was proposed by another group
(Friston et al, 1989). This approach avoided the need for an x-ray and established the
origin from the PET scan itself.

---

42 Talairach had been used by Roland and colleagues in the seventies, to transfer their images into
proportional format.
43 Greitz, who had written about the use of stereotaxic frames in the eighties, argues 10 years later that the
skills of a radiologist to perform this positioning are no longer needed, because with the help of
computerized methods to retrieve any plane in scans, reproducible alignment and reproducible fixation have
become unnecessary (Greitz et al, 1991). Furthermore, the work of the neuroradiologist is changing by
looking at new images, such as ‘mean’ anatomy images, which he/she compares to that of a patient, making
the same comparisons as in “the clinical situation which concerns the state of one individual compared to a
normal population (Greitz et al, 1991).” The material and cognitive component of the work of radiologist
has therefore changed as their context of work moves from an optical to a digital topical space.
The Fox method was attractive to researchers for a number of reasons. First, it was a highly objective method of localisation, in the sense of not depending on an observer. Furthermore, it provided, in theory, unambiguous localisation. In this Cartesian space, each point corresponds monosemically to given coordinates, and these points are labelled according to traditional nomenclature (see Figure 13). No one has to look at the image and pronounce a judgement on the anatomical identity of a structure. Furthermore, the labels of anatomical areas do not depend on gross boundaries visible on MRI scans, which meant that a more accurate localisation in the cortex could be made (Fox et al., 1985). The need to better localise in the cortex was increasingly important as the potential use of PET to study higher brain functions was explored. And as a matter of course for a research application, his approach also enabled comparisons between subjects, in standard space (Fox et al., 1985).

Fox’s application of the atlas was used in-house at St Louis and discussed at conferences before the method was set out in a publication. The technique had been announced in a response to Mazziotta’s editorial, as ‘echoing’ the recommendations of Mazziotta on the need for standardisation of data analysis. PET could not be understood by itself, although PET images were “seductive, appearing self-sufficient and inviting evaluation by visual inspection.” They also noted that this system need not change the ‘region of interest’ approach to data analysis which was then dominant: “It should be noted that although every pixel within the tomographic image is ascribed a stereotaxic coordinate, the grouping of these coordinates into regions of interest remains at the discretion of the investigator. (Fox et al, 1984).” Talairach was proposed as a solution to standardisation of anatomy-- the need for a structural baseline that would allow researchers freedom to explore function. It became much more, however, providing brain mapping with a way of conceiving and constituting a space of the brain in which to make measurements.

Some insisted on the need to take individual anatomy into account, or the need to further explore what a standard anatomy might mean. These recommendations for further explorations referred specifically to the study of anatomy that was becoming possible with MRI scanners. This new tool provided new kinds and new amounts of data about the anatomy of the brain. Because it did not involve radiation and was considered safe, it could be applied widely to the study of normal brains. Radiation or other risks involved in the technology’s use until then meant that they were applied only where clinical considerations warranted the risks. Studies on the variability of the brain’s anatomy were beginning to appear around this time. These various standpoints with regards to PET and anatomical context voiced in the workshop report, and the various strategies described earlier in this chapter can be contrasted in terms of varying definitions of anatomy: individual, standard, or variable. Privileging each of these has consequences for

---

44 See chapter four for a discussion of this kind of distrust of image data.
45 Ways of modelling data in three dimensions (corresponding to the space of the brain) were also being explored for other technologies in neuroscience, such as EEG, as computational power was becoming more widely available. See Gevins et al (1994).
the way scanning is performed and the types of questions PET investigations could answer as being clinically or research-oriented.

**Recommendations**

At the initiative of Mazziotta and Stephen Koslow of the NIMH, the issue of developing standards for PET scanning was addressed in a survey of all PET and SPECT centres around 1984. The issue of standardisation was then put explicitly on the agenda in a series of workshops held in 1985, to which a total of 25 centres sent representatives. Reporting on the workshops organised by Mazziotta and the NIMH, the call to standardise was made once again:

"Our ability to take full advantage of the power of functional imaging and to maintain credibility requires standardised, reproducible, and accurate methods of obtaining, analysing and reporting the resultant data as well as recognition of the limits of these approaches (Mazziotta and Koslow, 1987)."

If there was a consensus that the analysis of PET scans was best subsumed to the anatomical context, the ideal solution to this was still very contentious: "Anatomical issues remained the least well defined (Mazziotta and Koslow, 1987)." The workshop report, however, stated that "the major criterion for judging methods for anatomical localisation within PET images established by the functional imaging workshops was independence from the physiological image (Fox and Kall, 1987)." PET scans were therefore to be understood in anatomical terms but anatomy was not to be read from physiology. On the other hand, while functional images could be individually paired with structural images, this was considered to be cumbersome, costly and not in line with the goals of standardisation (Mazziotta and Koslow, 1987). According to a list of "criteria for the optimal solution to the problem of functional imaging acquisition" developed during the workshops, the solution proposed in 1985 by Fox et al was chosen as most suitable.

So within the strategy of using anatomy as a reference for PET, the Fox approach using Talairach provided anatomical localisation, without the need to make a second scan, and in a way that could be highly automated and standardised. But there were dissenting opinions in the workshop report, however, some of which clearly questioned the use of an anatomical baseline as a stifling standard. Each PET scan was related to the Talairach space, in order to have a shared anatomical baseline. For example, more clinically-oriented users of PET insisted on the need to take into account the anatomy of

---

40 This related nuclear medicine technology uses other tracers and does not produce tomographic images. It is considered to be much more easy to use than PET in clinical settings. Hardly any brain mapping work is pursued with this tool, however, and other technologies are more readily associated with PET outside the nuclear medicine context.

47 While the majority were North American, half a dozen European centres were also represented.
individual patients, and stressed individual differences in the brain, so that only individualised anatomical baselines would do. In spite of the workshop’s recommendations, a number of techniques for determining anatomical relevance of areas in a PET scans remained in use, determined by local research agendas and the specific clinical investigations being pursued.

**Aligning Brains, Averaging Brains, Subtracting Brains, Seeing Minds**

While Fox felt his method offered many advantages, and had received support form his colleagues at St. Louis and at least some backing during the workshops, there was no consensus around this method:

"The response, overall, was exceedingly negative. And that the usual objection that people would make were that the stereotactic coordinates couldn’t work because brains were not enough alike. And when you looked for assessments of how variable they were, there weren’t any. Because you can’t actually assess variability unless you have a standard framework. And so the argument to me seemed very circular...Another reason was that people said it would stifle creativity... Let’s not do it in any standard way because it might be the wrong standard way (Fox, interview).

In the same period, a prominent cognitive psychologist, Michael Posner, had joined the group at Washington University, and the uses of the Talairach atlas were expanded as they were applied to a different use of PET scans. This group began to average PET scans to be able to detect more subtle activations, since averaging scans improved the signal to noise ratio. By putting all PET scans into a similar space (a strategy proposed earlier as a solution to anatomical localisation), PET could be used to detect activity in the brain as it performed cognitive activities. By aligning brains, a better signal was obtained, and the brain in the course of producing the mind could be imaged.

In order to do this, this group used the method for anatomical localisation they had earlier proposed as a solution to having an anatomical referent for points of activation. By extending the logic of arrays, and manipulating them as grids rather than as landscapes. PET scans were standardised according to the Talairach space. This was done, however, for averaging purposes, not primarily for finding an anatomical label. The goal here was to improve on the functional information, by standardising the ‘format’ of brain, so that averaging could be performed.

---

46 See chapter 5, page 143, for discussions of how this also became an important avenue of research.
Figure 14 Use of Talairach Space for Averaging and Subtracting Activations

The use of the Talairach atlas is adapted to the averaging of activations. The Talairach space and the transformations it allows, rather than its anatomical information, become the motivation for its use.

The Talairach system was adapted from its earlier use, where it provided a space for the translation of physiology to anatomy, serving as a space in which to compare and compile different activations from different brains. The success of averaging in improving results was also argued to be a confirmation of the method for anatomical purposes. Here, the agenda focused on localisation of function, rather than anatomical regionalisation in a metabolic image. Fox recounts this shift:

“But what really turned the tide tremendously was when in 88, we published the method for averaging. And we demonstrated that in the standard space, you could average data and thereby could suppress noise and greatly improve the signal to noise and you could now discover things that you couldn’t discover before, so it
was useful. Before people were arguing about a principle, and I was arguing that we should report in a standardised way, so we could communicate with one another in a rigorous non-biased way. But that wasn’t a good enough argument. But when I told them they could see things that they couldn’t see before, [the] argument was over (Fox int.)

PET scanners were presented here as showing meaningful differences between different activations in the brain (by way of averaging and subtraction) rather than being meaningful in terms of a level of activity in an anatomical area.

Using the \( H_2^{15}O \) method, which allowed for shorter scans, of 40 seconds rather than 40 minutes as with the FDG method, Fox et al (1985) proposed that ROI could be defined physiologically, by means of subtractions of a rest state and a stimulated state. They published on this approach again in 1988, stressing the possibility of enhanced detection, when scans were averaged between subjects. The Talairach system was therefore used here as a tool for transforming the entire image (scan) into coordinate space, not simply as a look up table to report locations of physiological measurements (Fox, 1995)

To describe this change explicitly, comparisons between scans are no longer done solely on the basis of regions determined by anatomy. The region of interest can be identified based on the differences in activations between two scans, as an image of ‘change’, and further averaged between subjects. This approach is contrasted to earlier ones, where anatomy prevailed. Rather than being based on measurements in a region of interest, where the activity in a selected anatomical area is the focus of analysis, this approach identifies areas based on physiological changes between two scans.

The uses of PET therefore change at this point. In these studies, PET was described as tool for “mapping the functional organisation of the human brain” (Fox et al, 1988), no longer primarily for identifying metabolic states in relation to clinical agendas. While activities in the primary cortex had been scanned in some early experiments (i.e. visual stimulation), “higher order” cognitive activities, taken to show less activation, could only be mapped if sensitivity was increased.\(^9\) PET could therefore serve and extend Posner’s research interest in cognition, if more subtle activations could be detected. The “more subtle activations of characteristically human functions (e.g. language) (Fox et al. 1988)” were within reach, if inscribed in Talairach space.\(^{30}\)

---

\(^9\) This was also a way to reduce signal to noise ratio and expose subjects to less radiation (Woods, 1996) and enabled researchers to get more ‘subtle’ activations, where changes in blood flow were less than 10% rCBF (Aine, 1995).

\(^{30}\) Note that this subtlety of activations fits in with a hierarchy of brain functions, with motor or sensory activations considered more robust than more refined ‘mental’ events (calculations, planning, episodic memory, creative thoughts, etc). This hierarchy is sometimes sustained by evolutionary biology hierarchies about the ‘age’ of various systems in the brain. PET is said to have overcome a reluctance to map the higher functions (Kandel, 1991).
Significantly, rather than being evaluated along other methods relevant to anatomy discussed earlier, this method was compared to psychometric/psychological methods for measuring mental activity (for example, to averaging done in other studies of the brain, such as measures of event-related electric potential). In these studies, sequences of similar events over time are averaged, and the timing of the stimulus is used to link events. In averaging PET scans between different subjects, however, spatial markers are used. Anatomy, as far as it was still of concern in this research, was subsumed to the requirements for averaging:

"intersubject averaging requires highly accurate anatomical standardisation, capable of correcting for individual differences in slice orientation, brain size and shape (Fox et al 1988)."

Anatomy still figures, but insofar as it improves the goal of comparing PET activations, and any improvements to anatomical referents are geared to the elimination of individual differences, of anatomical idiosyncrasies which might obscure normal, generalizable cognitive data.

**That's Psychology!**

The methods used in PET experiments were therefore variously aligned during this period, to new applications and to older, clinical uses. The use of contrasting states was originally described according to the methods of analysis that had arisen out of metabolic studies; contrasting scans was simply a better way of defining ROIs, by doing it ‘physiologically’ rather than anatomically. But this strategy was quickly linked to the notion of ‘cognitive subtraction’ in subsequent experiments:

"So once we demonstrated that you could average, then you might get very subtle activations. That was very much the draw for the cognitive neuroscientists or the cognitive scientists. And that was definitely a big factor in Posner’s coming to St Louis. He came, I guess it was 86.... We could get lateral activations, language effects, we could get things that, areas that were quite removed from the primary cortex. And there were very nice responses when you averaged. And that clearly motivated Mike [Posner] to come down and take part in the venture. And once you have somebody as prominent as Posner joined in the enterprise, then it was immediately credible for all cognitive psychology (Fox, int.).

New kinds of experiments were being performed with PET. These were not scans of increased or decreased metabolism in relation to disease-relevant regions, but cognitive activations and localisation of structures and systems in the brain. The papers published in *Nature* and *Science* by Posner, Petersen, Fox, Raichle and colleagues are noted, especially by psychologists, as especially significant for changing the research agenda of PET. One respondent, while disagreeing with the actual findings of the experiment, was full of enthusiasm for the experiment itself, calling it
“absolutely the classic experiment in scanning that made others see what was possible with scanning. (Senior Researcher, trained as psychologist).”

And this researcher goes on to insist that what was interesting was not the claims, but “it’s that it was psychology (Senior Researcher, trained as psychologist).” This experiment, which relied on spatial normalisation based on Talairach to get high signal to noise ratios, and using a statistical approach to PET in which relative activations between two states were the focus of what was being measured, seemed to make the translation of cognitive tasks translatable into a PET scanning procedure seem feasible. Another researcher reflects in similar terms about this period:

“We were quite aware [around 89] that in America, at St Louis, [they] had developed a new of looking at PET scans using statistical techniques, and had in doing that shown some quite basic things, but interesting phenomena. You could take a number of tasks, psychological task, dissect them and find out what was the sort of component that was different between these task… Cognitive subtraction, that was the buzzword (Senior Researcher, trained as psychiatrist).”

The focus was therefore shifting to understanding PET data as showing contrasting units of cognition which could be detected in the brain. PET measurements were making sense in terms of psychologists’ phenomena:

“… this was directly taking a cognitive psychological model with all these boxes, as I’m sure you know, saying this box is in this bit of the brain and we’re able to determine this by doing PET scans…. So I was obviously very excited about this, because my work was full of these boxes and I had thought in this case I can find out whether the boxes exist and where they are (Senior Researcher, trained as psychologist).”

It therefore seems that the use of Talairach was only somewhat useful for anatomical localisation of physiological data, but that the system of comparative grids was very powerful for pursuing cognitive psychology experiments. How so? In the stream of research that investigated clinically-relevant questions, metabolism and anatomy were to be correlated, and PET scans were analysed as regions of interest. Talairach did provide a standardised mode of establishing these correlations, but Talairach presented a version of anatomy which seemed impoverished to clinical investigators who wanted individual anatomy, or anatomical referents more sensitive to variability between individuals to be taken into account. In these cognitive experiments, differences between scans in this new experimental approach were not longer high/low metabolism, but a trace, measurable across many brains, of functional performance of cognitive tasks. In this psychological context, functional anatomy is not the pendent of structural anatomy, but is rather linked to the performance of tasks or processing of stimuli, as defined by cognitive psychological concepts. To put it another way, PET becomes the hard evidence, involving the brain in the study of the mind, rather than constituting the fuzzier metabolic data to be
correlated in terms of anatomy. The brain and the mind met as arrays in Talairach space, with anatomy as a useful intermediary, rather than as the ultimate destination as PET's referent.

**Anatomy and Talairach Revisited**

The community of researchers working around PET thus came to include cognitive psychologists and neuro-psychologists. But "anatomy" remained an important issue for many investigators who had been working with PET. A second series of workshops was held in 1989 and its report published in 1991. The interpretation and analysis of PET results were still high on the agenda. The report observed that standardisation had not yet occurred (Rapoport, 1991). Six strategies for 'regionalisation' were enumerated in 1991, and two schools of research were identified, one focusing on using PET data alone and identifying clinically significant 'patterns' and the other on using MRI with PET (Mazziotta et al., 1991). The search for patterns, rather than the use of quantitative measurements was condemned by physicists working on PET and some research-oriented physicians in nuclear medicine, as a "flight from quantitation", a flight from the very element that these researchers felt was the 'hardness' of PET. Those seeking patterns were oriented to the clinical usefulness and feasibility of PET scanning. The report also explicitly addressed a dissatisfaction with PET, felt by academic neurologists and neurosurgeons, expressing surprise at this, because, the report argued, the proper tools were only just coming into existence. The "publication of ambiguous, uninterpretable, or conflicting results from established PET centres has further contributed to the disrepute of PET as a clinically relevant imaging modality (Rapoport, 1991)."

In terms of the standardisation of anatomical referents, the report embraced the Fox method, but included dissenting opinions, including a challenge to the notion that the visual was inherently non-objective. It was argued that visual evaluation made it possible to deal directly with the physiological image, rather than choosing, a priori, the older traditional anatomical referent, while physiological landscape of the brain had not yet

---

51 The 'big science' aspect of PET meant that (ideally) large numbers of researchers worked with a single scanner, so that most often during this period, psychologists established working relationships with PET centres rather than establish their own. A common scenario seems to have been the involvement of cognitive psychologists from academic departments at universities where the medical faculty or teaching hospital had a PET scanner. The desirability of combining institutions and specialties was highly recommended to health care service managers (Frick et al, 1992) Funding from the McDonnell-Pew Foundation played an important role in forming cognitive neuroscience research centres. Shortly after this, in the early nineties, the development of functional applications for MRI scanners multiplied the numbers of centres where psychologists could get involved, as well as making it easier for all kinds of researchers to do research scans on normal subjects.

52 I return to this particular episode in chapter 4. The clinical investigations which some saw as 'fleeing from quantification' in the late eighties have indeed parted ways to some extent from brain mapping work and research. Some use largely visual strategies, identifying patterns that can be associated with particular conditions (Gilman, 1998 a, b). Others have developed atlases for visual diagnosis, containing representations based on PET scans represented on MRIs and labelled in Talairach (Minoshima et al., "Stereotactic PET Atlas of the Human Brain: Aid for Visual Interpretation of Functional Brain Images").
been investigated (Clark, 1987). Recall that in the first series of workshops, it has been suggested that a combination of systems that consider both individual brain anatomy and coordinate systems might be the best approach (Mazziotta and Koslow, 1987). But the system of Fox et al was described as most desirable at that point in time because of the greater standardisation it enabled. Some participants to these workshops seem to have feared that PET would be abandoned prematurely, and this may have fuelled a further desire to standardise analysis. It was in this context that attempts were made to reconcile the Talairach coordinate space and anatomy, and that a version of anatomy suitable for this purpose was sought by these PET researchers.

MRI Anatomy

In 1989, the tension between the anatomy of the individual brain and the need to use a standard space was once again noted: “the combination of stereotactic approaches (Talairach et al, 1967) with individualised neuro-anatomy, obtained from structure function matching approaches, may lead to the most automated yet individualised method available” (Mazziotta et al. 1991). This report contained not only statements about the desirability of bringing together standard anatomy and individual anatomy, but it also presented methods for achieving this. At this point, although the use of co-ordinate space and of anatomical referents were still considered separate approaches, the understanding of anatomy was beginning to be linked to the terms of co-ordinate space. Reporting on this workshop, the use of Talairach space was recommended for subtracting images. The use of Evans’ or Mazziotta’s 3-D MRI volumes (‘VOI’) was recommended for establishing the anatomical referent:

“either the Mazziotta or Evans approach should help to create a VOI atlas of PET data in health and disease, which, if placed in a standard co-ordinate system, could be digitised and transferred between institutions (Rapoport, 1991).”

Anatomy, as defined using MRI, would therefore allow both the goal of anatomical standardisation and of measuring anatomical variability. Translation of various versions of anatomy also seemed a promising avenue, so that coordinate space also became relevant to issues of anatomical correlation, on top of its usefulness for studying cognitive activation. While the notion of a ‘coordinate space’ became common to the various efforts in developing uses of PET scanning, this also meant further reworking of the ‘Talairach coordinate space’ itself, to incorporate a better anatomical referent.

For those primarily interested in cognitive activations, improving anatomy beyond the Talairach atlas also became a priority. The impetus for this was a case where some of the most spectacular findings of PET research in terms of finding substrates to mental activity, were the subject of debate and a retraction in Science. Using only the Talairach atlas, researchers had localised a particular activation that correlated with panic attacks (Reiman. 1989). This work was widely hailed as one of the great success stories of
the use of PET for the study of the brain. Further work by other researchers using MRI as anatomical context to analyse the PET scans found that the activation detected fell outside the brain, and was the result of increased blood flow due to teeth clenching (Drevets, Veideen, Macleod, Heller, Raichle, 1992). While Talairach as a space to average was yielding great results, Talairach as anatomical reference had proved its shortcomings in this case. The use of the anatomy provided in the Talairach atlas alone was therefore found to lead to “overinterpretation”. So if the use of stereotaxic space was taken to have clear advantages in getting better functional information by allowing intersubject averaging and subtraction, there were still arguments about the need to improve the correspondence of anatomy and function. As demonstrated in the correction episode above, MRI was felt to be a better, more accurate marker of anatomy than the use of the Talairach anatomy. Yet, while PET scans could be related to the MRI scans of individual subjects, comparisons across subjects were desirable and best achieved using a standard space. Those interested in anatomy re-directed their efforts to improve localisation in coordinate space. The MNI groups, which had been working on templates to overlay onto MRI and PET for individual subjects, then began to develop ways to compare MRI to PET using, not as a template, but using Talairach as intermediate space. Mazziotta et al proposed techniques for ‘merging’ different data within subject and then between brains, using coordinates. They used the outlines of scalp or brain as matching markers, but the transformations were all in terms of coordinates of scans. Digital strategies were therefore developing, as was the notion that different types of data, once in common coordinate space could be translated into each other.

In 1992, the Evans group (at the MNI) suggested merging averaged MRI and averaged PET into Talairach space. This was presented as an approach to analyse normal brains, specifically for use in interpreting cognitive activations studies. These publications also discussed anatomy using new concepts such as variability, and ‘true mean anatomy of group’. They argued that more sophisticated versions of anatomy than the original Talairach paper atlas alone could benefit both clinical work and cognitive studies – they specifically referred to the issue of ‘extra-cerebral peaks’, and overinterpretation.

In these approaches, both PET scans and individual MRIs were transformed to be compared into a standard grid defined by the Talairach space. So while a standard space was used to relate different types of information, individual anatomy provided the anatomical context. In the development of these techniques, there was a parallel treatment of anatomy and function in the sense that both were averaged in coordinate space and found to be ‘improved’, becoming more representative and more significant through this process.

---

3 This research was considered a big breakthrough for biological psychiatry, where a condition without clear etiology was shown to be correlated with a specific physical trace. See Ackerman (1992).
Anatomical reference
\((x, y, z) = \text{label}\)
(automated, linked to average brain)

Averaged PET/fMRI scans

Average dd PET/fMRI scans

V V
X X
/ /

Other types of functional
or structural information
(MEG, etc) in HBP

Averaged MRIs

Figure 15 Uses of the Talairach System

The use of 'Talairach' now involves a complex system of representations which are made equivalent in the coordinate space. Talairach is now used for averaging and subtraction, for establishing an anatomical framework based on MRI scans, for integrating all levels of data once made comparable by being inscribed in the same space.

The workshop report also contained suggestions that coordinate space might be useful as a framework, beyond simply being used as an atlas. Echoing the changing
research agenda with PET, this report also suggested that ‘patterns’ of metabolic activity might be related to cognitive activity, and usefully placed within a framework:

“Large sets of PET-derived data, placed within identified ROIs in a standard coordinate framework, provide an opportunity to examine patterns of brain metabolism and flow, in addition to regional values taken one by one.... The patterns that are derived can be analysed and interpreted in terms of brain organisation at various levels in higher primates...these systems overlap and represent in humans the ‘internal structure of specific mental activity’ (Luria, 1973) (Rapoport, 1991).”

These recommendations for integrating data, both anatomical and functional, form the beginning of the work on databases and atlases further described in chapter 5. For the purpose of the argument unfolding in this chapter, the significance of these recommendation is that they formulate the desirability of achieving greater standardisation, and of relating both activation and anatomy to Talairach/coordinate space. Thus, the concerns of cognitive psychologists, and neuroscientists to improve localisation of function and the need to study function/structure relations in general gave the impetus for improving the manipulation of brains scans in terms of reference spaces.

Talairach: a Digital Space Big Enough for Disagreement

The development and spread of Talairach did no unify all PET users behind a single definition of anatomy, and indeed, clinicians and surgeons and psychologists maintained their concerns that a proper anatomical correlation should be established with PET. Furthermore, while these groups could be said to be concerned with ‘variability’, they were coming at this issue from diametrically opposite directions. Surgeons wanted to have functional information more closely tied to the particular brain on which they were going to operate, while cognitive psychologists wanted to overcome this variability in order to be able to make statements about the human mind, as found in the brain, in general. But within the parameters of the framework provided by the Talairach space, these various versions of anatomy could be improved and integrated. Talairach, once fully digitised, provided a way to translate into PET experiments both the investigation of a specific patient’s brain, or the relation of the brain to a very abstract, ‘human’ cognitive function. PET in a Talairach space serves to put both the study of the brain and mind in a digital context. In turn, the Talairach system functions as boundary object, a version of the brain which can be appropriated by various disciplines and which can accommodate their respective object of research.

By the early nineties, as the success of the Washington group was widely celebrated and had inspired many other cognitive psychologists, a new agenda for PET research was added to the neurological and clinical investigations of the early eighties. Shulman also notes this shift, from sensory studies to “the ability to study cognitive
stimulation [which] informed us about the mind, and therefore the mind, in addition to
the brain, was becoming accessible to study (Shulman, 1996)." The functional brain was
to be a source of data for the study of the mind:

"The combination of cognitive and neuro-biological approaches, of which this
study is an example, has given us information about the functional anatomy of
perception, attention, motor control and language. As these endeavours proceed,
solutions to the problem of mind-brain interactions that have intrigued us for so
long should be illuminated (Petersen et al, 1988)."

In terms of research agendas too, there were significant differences in the orientation of
various groups. This is sometimes described as 'those coming from the brain end and
those coming from the mind end'. But, as this colloquial description implies, there is
at least a feeling that work proceeds along an axis, that provided by the Talairach space.

Using Stereotaxic Space: Co-existing Versions of the Space inside the Skull

So, while, on the one hand, the question of what constitutes proper anatomy has
exploded as Talairach has been pulled apart, the idea that anatomy could be related to the
coordinate space in which PET scans were analysed unified these efforts, or at least made
them comparable. Besides anatomical referents, which had long been a key issue in the
interpretation of PET scans, other aspects of the Talairach system were also revised. The
Talairach atlas, as it was known in its paper form, came to be de-constructed by
researchers into various parts: the x, y, z. Cartesian space approach, the methods for
transforming brains to that space, and the 'target' brain to which all others were to be
transformed. These improvements are best understood by contrasting the original use of
the Talairach atlas (for interpreting structures deep in the brain as investigated through
pneumoencephalography, as a preparation for neuro-surgery) to the project of mapping
the mind onto the brain (for interpreting the highly variable cortex, as investigated by
PET, by cognitive psychologists, psychiatrists and neurologists). Shifts in location (clinic
to lab), purposes (from surgical intervention to investigation), in sensitivity (low to high
resolution), in application (from individual patients to populations), in anatomical
location (from structures with low variability to high) are all aspects that led to the
adjustments made to the atlas. These elements must be considered in order to understand
the development of a digital context in which to pursue this work.

No one likes Talairach, but everybody has to use it. 54

In the last part of this chapter, I will briefly review the main areas of work which
constitute the new context of PET within the Talairach 'system', and show the
surprisingly broad range of questions posed in terms of this system. As mentioned, a

54 Senior Researcher, on Atlasing panel at Conference on Mapping of the Human Brain, Copenhagen, 1997.
range of sometimes contradictory criteria for localisation have been formulated in the
course of the development of PET. The choice of a target brain in the original Talairach
atlas has been challenged on a number of levels. Some have argued that it is not properly
representative because it cannot encompass variability:

“I’m very concerned that in the old days, the method of going to the atlas, in this
case, the Talairach atlas, devised by Fox….now we’ve got to grow up and throw
away the Talairach atlas. We know to much about the variability of the location
and extent of brain areas to be going to the brain of a single female, which turned
out to be unrepresentative of the human brain, not because its a female brain, but
because of this particular one. And we are going to need probability atlases of the
sort that are being developed in America …(Senior researcher, trained as
psychologist).

If the target is no longer a single hemisphere of a single brain, the probabilistic atlases are
also being built in terms of a coordinate space. Relations between arrays (representing
various anatomies) are quantified in this digital context, and replace the single brain that
functioned as landscape of reference.

The Talairach atlas has also been criticised as representing a typically
Western/European brain. There has been at least one instance where ethnicity has been
the basis of a the production of a different standard atlas. Kanno et al (1992) have
developed a Japanese brain, and its use is justified by arguing that

“there is a considerable, systematic difference between the Japanese brain and the
Western brain” and “this method has been shown to be effective in coping with
the problem caused by the individual morphological variation, such as
hemispheric asymmetry and front-occipital disproportion, which is common
among Japanese subjects (Cheng et al, 1995).”

There are a number of other discussions about the parameters of interest in making an
anatomical reference. For example, the issue of the ‘Japanese brain’ can be labelled as the
result of “increasing genetic distance between subjects”(Wood, 1996). But, it is a problem
which researchers argue can be solved by using a more sophisticated model (Woods,
1996), and ‘simply’ adjusting the target that is to be selected for transformation into the
Talairach space. The traits that affect the choice of a target brain are extensive and
discussed in more detail in chapter 5, but include “sexual dimorphism”, age, ethnicity
and “other characteristics” also mentioned (Toga and Mazziotta, 1996).

In terms of how to achieve a proper correlation between function and structure,
the original Talairach has also been found wanting:
“Talairach was a surgeon and he didn’t know about the brain. So we shouldn’t say it was the angular gyrus when what we mean is that we looked it up in some atlas (Comment from the floor. Conference on Mapping of the Human Brain).”

Not surprisingly, neuroanatomists, neurophysiologists and surgeons all have complaints about the use of Talairach for localisation. These various groups work in a different ‘version’ of anatomy: the neuroanatomist in terms of gyri and sulci, the neurophysiologist at the micro level of cells, and the surgeon, in ‘native’ space, not in standard space. But significantly for a growing stream of research, disagreements and solutions can at least be articulated in terms of a common reference, the Talairach space. This is rather the creation of a space in which to align various types of data, which by virtue of the integrative possibilities of Cartesian coordinates, seems to offer the possibility of unifying and compiling data. Databases and atlases are built using the Talairach conventions, so that other levels of anatomy, for example the cellular structures, or other kinds of activity (information from fMRI, or MEG or EEG) are being put into Talairach space and related to each other. While the method is adequate for comparing normals, some argue that “reference to a standard atlas, which assumes proportionality and symmetry, will never be ideal” (Friston et al, 1989). Solutions proposed to this are to improve on the ‘target’ brain of the Talairach system, and to base this target on more ‘valid’ assumptions.

Warping Brains in Talairach Space: Individual, Variable, and Standard Brains

One of the areas of research in brain mapping is the ‘warping’ of brains from native space to standard space. (See Figure 7, page 23, showing brain warping.) While the Talairach atlas described a method for doing this using pen and paper, and dividing the brain into 12 quadrants, current methods transform voxels in very sophisticated ways, using computerised algorithms:

“One of the original motivations of going to non-linear deformations was to try and further reduce the differences between brains once they were put in a standard space. Such that in theory, your brain and my brain could be made to look completely identical… the idea here was that if there were any differences, in functional neuro-anatomy, those aspects of that variation which were in fact just differences in [inaud]…morphology would be removed. Our brains could be made completely identical anatomically and then any functional mapping on my brain and your brain would be different, you could see they were different for functional reasons not for gross morphological reasons….(Evans, int).”

These efforts address the issue of variability, and the need to have a standard, a baseline from which to compare different brains. If one gets rid of anatomical variability, then one can compare functions. But anatomical variability itself can be of interest:
"Having got rid of it, you still want to, for other scientific reasons, you may want
to capture and quantify variability (Evans, int)."

The grid space enables researchers to track and quantify variability. Digital space, and the
use of computers in these transformations are essential to the increased complexity of
these transformations. More complex transformations are more sensitive, and greater
sensitivity is better. Indeed, one researcher affirmed that

"Talairach would have done it if he had had the tools. He understood this but
didn't have the tools (Evans, int)."

While the original target brain and methods for transforming one brain into another have
been abandoned, this group argues it had "kept the spirit" of Talairach. Clearly, tools,
applications and context have all changed as Talairach has been digitised and as various
groups in functional imaging have invested in improving the possibilities of translation
offered by the coordinate system. Talairach has become an important collaborative tool,
standardising not only results, but much of the work in the brain mapping community
itself.

Places in the Brain: Call my Name or Dial my Number

Besides being familiar to a small number of neurosurgeons, who again, would use
Talairach in relation to the 'native' brain space of their particular patient and not in terms
of average or probabilistic anatomy, the use of Talairach co-ordinates is fairly confined
to the imaging community. At the beginning of this chapter, I noted how brain mappers
were sometimes self-conscious about their use of coordinates in place of using traditional
nomenclature. The experimental and conceptual reasons that have led to the particular
version of anatomy for brain mappers have been analysed in this chapter. But while brain
mappers have embraced Cartesian addresses for points in the brain, they are still aware of
the advantages of making their work accessible to other domains of neuroscience, by
means of translating coordinates into labels. Mappers explain that coordinates are
essential to their work:

"Neuroanatomic labels are used to communicate, whereas maps use coordinate
space to quantitate. Equating the relationship between neuro-anatomic labels and a
Cartesian (or polar) coordinate system is one the by-products of a map. The
principles of most brain maps (and systems based on them, e.g. stereotactic
surgery) depend on a spatial structure defined by the Cartesian coordinate
system....To define a location, three coordinates must be specified, each
describing the distance from a plane of origin references to a reliable set of
anatomical points." (Toga and Mazziotta, 1996).

Brain mappers also find many advantages in the use of coordinates rather than
labels: Because it is a quantitative, numerical system, Talairach is said to be
unambiguous, unlike conventional terminology (Fox et al. 1995). This argument makes sense only insofar as the points described by coordinates (3 numerical values) are considered monosemic indications, referring to only one place. In contrast, there are a number of nomenclatures, many ways of naming a place in the brain. Furthermore, mappers object to using gross anatomy as a reference because of the need for a neuroanatomical expert to segment (label) the image:

“At best this is labour-intensive and costly. Far more troublesome is the observation that even trained experts are highly unreliable at identifying major landmarks (Fox, 1995).”

The relation of anatomy to coordinate space, on the contrary, can be built into automated systems which transform the spaces of scans, assigning in the first instance coordinates to voxels, rather than names to anatomical areas, and are in keeping with ideals of objectivity and automation, since they rely less on an observer’s skill. Further highlighting the importance of the principle of a coordinate space which can be ‘filled’ in, mappers insist that there is no correspondence between these anatomically visible areas and functional areas, as Brodmann warned (Fox, 1995). In this logic, a ‘neutral’ quantitative address for a location in the brain can be further given anatomical or functional identities, without one type of data prevailing over the other.

But as mentioned earlier, the use of coordinates is sometimes bewildering to outsiders or newcomers, and there have been efforts to further relate the x, y, z anatomy to traditional nomenclature, so that “anyone can navigate the Talairach spaces (Fox, 1995).” So while mathematization of space enables brain mappers to manipulate various types of data in a similar space, they still must relate their work to the still-dominant, traditional understanding of the brain as textual labels and names of areas.55

After Meaning Comes Significance: Statistics in Talairach Space

Other aspects of the analysis of PET scans were also developed, besides the question of anatomical relevance. In the early, ‘metabolic’ investigations with PET, PET measures indicated the level of metabolic activity in selected areas of the brain (mostly glucose). This involved arterial blood sampling, a relatively complex and invasive procedure. Again, this meant correlating the measurements of the PET scanner itself with

55 Braintree, for example, assigns labels to coordinates, and further links the terms according to the NeuroNames nomenclature developed by a neuroanatomist, who ‘painted’ all gyri onto a brain and incorporated it to Braintree, which relates nomenclatures. She is currently developing program so that when clicking on a term, the structure will appear, and alternately, to click on an MRI volume and have the label:

“Eventually, it would be good to be able to do this with functional MRI and PET data. So people who do PET studies, they should click on the area and be able to have an MRI with a pattern of activation on it and to get the name of the structures.”
another set of measures, based on blood samples. In the mid-eighties, following the development of another tracer with a shorter half life ($H_2^{15}O$), it became easier to make multiple scans.

Fox et al (1984a) proposed a ‘relative’ understanding of PET scans: understanding measurements in relation to other measurements of metabolic activity in the brain, rather than in absolute terms in relation to blood values. That means that PET scans could be understood as indicating change between the rest and activation state. Each subject could be her own control, by undergoing a rest scan. This meant that PET scans became images of change, of increase or decrease of activity, rather than absolute measurements of levels of metabolic activity, calculated from the detected radioactivity. When making images of change between conditions and dealing with activations that produce only subtle change, averaging responses across subjects increased the significance of PET scans. This approach to scanning involved complex statistical calculations in order to establish the significance of change, and the relation of local and global changes (Friston et al. 1990). Concern with ‘significance’ intersects with the earlier discussion in this chapter of the averaging of scans. And as discussed above, in order to compare activations across subjects, Talairach coordinate space provided a useful tool. Thus, this stream of work too ended up making use of the Talairach space in order to improve PET scans as measures of functional change.

As research agendas came to include and gradually focus on exploring cognitive tasks which produce these subtle changes, PET scans came to be understood as maps of change in relation to activation paradigms or stimuli, rather than detections of metabolism, or even ‘scans of the brain’. When asked how he would compare a CT scan and a PET scan, a researcher answered that

“Well, a CT scan is just a description of a brain, all the slices of a brain. A PET scan has been analysed in SPM” (Senior Researcher, trained as psychiatrist).

A PET scan is therefore an image of statistics, the result of data tested for its significance. A statistical understanding of scans led to the development of ‘analysis packages’, the best known and most widely used being ‘SPM’.

While some labs devise their own programmes, often also using a ‘Talairach approach’, the two main tools distributed in the brain imaging community both reinforce the use of Talairach. One is an atlas based on averaged MRIs, originating form the Montreal Neurological Institute, and sponsored by the Human Brain Project. The other is a data analysis program called SPM, distributed by the Wellcome Department of Cognitive Neurology in London. The SPM program offers a number of statistical tests, to be performed on voxels which are organised in a volume defined by the Talairach space. SPM eventually incorporated the MRI atlas as its anatomical template. Again, the use of coordinate space enables research around functional imaging that address topics as

---

63 Recall that at the 1989 workshops, a part of the PET community was moving away from quantitation (Strother et al. 1991; Carson. 1991).
diverse as statistical validity of change in relation to cognitive ability and anatomical localization to be brought together.

Towards a Model of the Brain

Some brain mappers have emphasised continuity with the Talairach atlas, stating that “the Talairach is most properly viewed as a modelling construct, (rather than as an atlas or collection of atlases), a reporting standard, or a class of analytic algorithms (Fox 1995).” Indeed, its unifying role is becoming increasingly prominent, but it has been considered all of these things (atlas, standards, etc) and only very gradually, over the course of ten years, has it come to be seen as a model.  

“As all observations are referenced to the same spatial framework, they collectively constitute a 3-D model of the human brain that is continuously updated by the research community itself (Fox, 1995).”

This argument is made not only for anatomical data, but also for activations. Raichle, who was involved with the first applications of ‘averaging’ of functional activation insists that this strategy was not followed just to overcome the limitations of PET’s sensitivity, but also because “at the outset our objective was to understand general organising principles of the human brain that transcend individual differences (Raichle, 1996a).” By averaging, a general principle arises, beyond individual idiosyncrasies.

The many episodes and streams of research described in this chapter around scans should make it clear that the use of Talairach, currently constituting a ‘lock-in’ in the brain mapping community, is the result of its usefulness for collaborations. Its adoption is shaped by its function as a boundary object, uniting brain mappers around a similar space, rather than the progressive implementation of an ‘original’ concept—though such a linear development has been claimed:

“Thus, the concept of a cumulative brain model implicit in the use of Talairach space and clearly enunciated by Talairach nearly three decades ago, is becoming an electronic reality (Fox, 1995.)”

57 There have also been proposals to use a polar space (as opposed to the Cartesian space of the Talairach system). The application of a polar system involves ‘blowing up’ the brain into a sphere. A polar space is considered more appropriate for showing cortical positions, and will also show distance between points on two sides of a sulcus, which a volumetric space such as Talairach doesn’t. This system is less useful for working on non-cortical areas—areas that are ‘buried’ not on the surface of the cortex. The most prominent surface systems have been developed by van Essen and Drury, for the macaque monkey and Visible Human data, focusing on the visual system, and by Brinkley, Ojemann and others (1997), whose surface model focuses on naming areas on the cortex. See Figure 6 The volumetric “canonical brain”, and the flattened cortex of the 2D brain.
As this chapter details, it has been a long road, from an implicit concept to the shaping of standard tools, and new research collaborations.

**The Mercator of Brain Map Projections**

The adoption of a coordinate space for describing data was therefore given its greatest impetus by being embraced by researchers pursuing cognitive experiments with PET. It enabled comparisons between subtle cognitive activations, and the exploration of the mind in the brain. But Talairach space also gradually came to serve the needs of other researchers—neurologists, neurophysiologists, and clinicians—in addressing the notion of an 'anatomical baseline' for interpreting PET scans. Indeed, it transformed the notion of a baseline as an anatomical landscape, as a hard bottom onto which to overlay a metabolic map. Rather, Talairach space came to be seen as a standardised space, and a system based three-dimensional coordinates, in which each x, y, z position represents a voxel. This voxel can then be labelled with an anatomical value, a statistically validated activation value, etc. There can therefore be multiple versions of this space. In theory an unlimited number are possible, but in practice a select few versions are built (these are discussed in chapter 5). Once data is put into coordinate space as a value, it becomes a question of the right algorithm—universal translations (Haraway, 1991) require but the right encoding.

---

**See Buschbaum (1995) for a commentary using a wealth of geographic metaphors.**
Figure 16 The brain as a percentage of MRI and PET

This figure represents the tool interface used in the analysis of some activation experiments. The first row shows PET data, the second MRI, and the third the combined view of structure and function. A pink ‘slide bar’, similar to the more familiar ‘brightness’ or ‘contrast’ bars on computer and television screens, allows the user to display the brain along a continuum, from 100% PET to 100% MRI. Here, the third row shows 50% PET and 50% MRI, but any percentage can be displayed, from 0 to 100%. Once registered in Talairach space, the brain’s activity slides seamlessly into the brain’s structure.

Reproduced courtesy of BIC/MNI and David MacDonald.

But, again, which and whether translations are pursued remains negotiable, and as we have seen, disciplinary agendas weigh heavily in this process. Expanding on the concept of trading zone proposed by Galison, Loewy further suggests that there may be various patterns in the ways communities share boundary objects (such as Talairach), and that the zones ‘between’ scientific cultures might be characterised as trading, pidgin or Creole zones. Using Loewy’s typology of intercultural relations to label the developments in brain mapping, there has clearly been the creation of a pidgin zone, where a language is neither that of the neuroscientists, nor of the neurologists—where the language spoken is that of x, y, z locations in the brain. Whether this pidgin zone might become Creolised, the native tongue of a group, remains to be seen. But the investments described here might indicate that a new community is indeed forming. The opinions of brain mappers themselves seem divided. While wishing to maintain collaborations, some want to see particular patterns of exchange, where the neurosciences might increase their influence in relation to the cognitive psychologists who have had too dominant a role (Friston, 1997; Shulman, 1996), and bring functional imaging into the mainstream of neuroscience. Others want to see a coming together of researchers in the area of brain mapping, and to see this enterprise institutionalised, through the sharing of common
resources and tools for communication particular to functional brain mapping (Fox. 1993; Mazziotta int.).

Interestingly, these issues often arise in relation to Talairach and standardised space. The 1998 International Conference on Functional Mapping of the Human Brain implemented the use of Talairach references in the submission of abstracts to the conference. The director of the laboratory hosting the conference has hinted that there is a lock-in, with regards to Talairach and that other systems can hardly compete with the “ubiquity” of the Talairach convention. While this submission strategy was not used for the 1999 conference, there were proposals during the conference to make increased use of this format, as a way of giving increased value to the abstracts by correlating/integrating them digitally, so that one would come away with an integrated view of the brain rather than a catalogue (Mazziotta. int.). Discussions focused on the need for the Organisation for Human Brain Mapping to provide more leadership in issues of standardisation for the sake of efficiency than has been the case up to now, as well as counter-arguments that ‘peer-review’ and scientific quality should be the only mechanisms put in place.  

The key concept in brain mapping is that of a universal stereotaxic space.

To return to the larger issue of the new objects arising from this scientific endeavour with which this chapter opened, after about ten years of functional studies, brain mapping researchers are making claims about their abilities to ground functions of the mind in the brain. This is the result of collaborations between cognitive science and the sciences of the brain which have built a new understanding of behaviour. It is an understanding which makes sense to neuroimagers because it links the perceived empiricism of the neural sciences with the sophisticated understanding of behaviour of the cognitive sciences. At the level of research, it is an understanding which makes sense in terms of the construction of a space for the mind, which can be translated into the space of the brain, and of a project of exploration that defines a territory to be mapped even as it sets out to investigate it. Making PET scans meaningful is not so much establishing a window on the brain, through which the mind can be seen by cognitive psychologists. It is rather developing and validating a kaleidoscope of mutually constitutive versions of the brain in a standard space, in which the various versions of brain/mind data can be meaningful to the many groups involved in functional imaging. It is in this sense that the brain becomes virtual in brain mapping; it is measured, known and used as a standardised construct in digital space, and new views of the brain can be integrated, given the right algorithm.

The development of these conventions in a digital space makes this case a particularly interesting one. First, because it shows the gradual shifts that occur in interpretative and contextualising work, from optical ways of working (physical markers

---

60 These tensions could be described as contrasting views of brain mapping endeavour, as a cutting edge exploration or an exercise in surveying.

61 From a proposal submitted to the Human Brain Project by the Consortium for Human Brain Mapping.
to compare scans as snapshots, visually identifying landmarks) to more digital ones (voxels being translated based on quantitative values, thresholds being set to evaluate significance). The development of Talairach conventions also highlights how particular versions of common scientific notions, such as sampling, objectivity, standardisation can be contested, and only gradually comes to be embedded in new digital tools.

Therefore, if such a dialogue between these disciplines can occur, it is in large part as a result of the co-ordination of many different representational spaces for the manipulation and testing of results, making the link between brain scans and mental functions possible. Through the process of developing standardised spaces and representations for manipulation, a new object emerges at the juncture of the cognitive and neuronal sciences—the ‘virtual brain’. At the same time, the basis for a ‘physical mind’ was also laid in the standardisation of a digital space for reporting results. The exploration of the mind-in-the-brain in functional imaging will be the subject of the next chapter.
Chapter 3 Maps of the Mind-in-the-Brain

Seeing the Living Brain... Seeing One’s Life in the Brain

One of the liveliest events I attended in my travels in the brain mapping community was a ‘wine and cheese’ that followed a presentation on mapping of “language areas” in bilingual subjects. The researcher presented findings where concentrations of activity in the brain could be found when subjects listened to one’s native language, but where no such concentrations could be found when subjects were listening to a second language. The audience had much to say about these results, but these comments were not so much focused on the experiments themselves; rather, people were talking about their own lives, about their own experiences of childhood and bilingualism.

Before further describing the results, I want to note that this finding was strongly shaped by the methodology of brain mapping experiments. Scans are averaged, so that signal to noise is improved. This is taken to mean that areas common to all subjects will reinforce each other, and that idiosyncratic activities in which the subject might have been involved (i.e. the subject might be doing the task in the scanner, but also thinking about radioactivity, or being bored, etc) will be ‘averaged out’. In this experiment, on late bilinguals listening to a second language, the activations themselves were averaged out, suggesting that localisation in the brain was highly idiosyncratic, to the point that areas in subjects’ brains were so different as not to overlap and produce a significant signal-to-noise ratio. A second language, according to the logic of this experiment, is not systematically embedded in the brain, except for highly proficient speakers (i.e. professional translators, studied in a different experiment). The researcher doing this presentation suggested that there might be a deep biological reason for this: the (evolutionarily advantageous) need for a baby to stabilise one language.

As I mentioned, the wine and cheese that followed was extremely animated, as a room full of academics, many of them upwardly or internationally mobile, or trans-culturally married, debated the findings. But the degree of animation of these discussions was not the only noteworthy element: the arguments used were highly biographical, comparing the age/exposure/proficiency between one’s children, or one’s own language abilities in relation to family members. Exiled researchers discussed the proficiency that remained, even after decades of absence, in one’s dialect, in comparison to decreasing comfort in the ‘national standard’ language. These discussions arose because development was being mapped—the slides on the screen were the traces of early biography, in which adults projected their own histories, intimate arrangements and accommodations within couples, and their own aspirations for their children as worldly upper/middle-class parents. This brain mapping experiment stimulated the listeners not only to consider topics and theories about mind and brain structures, but also to rethink
elements of their biographies and contexts, as well as linguistic and parenting abilities through functional imaging parameters. In other words, the audience reflected on highly complex aspects of their own lives in terms of their effect on brains. This event highlighted the dynamics of brain mapping in a rather intriguing and dramatised, if not quite dramatic way.64

This chapter will explore how maps of the mind are having a growing effect on a number of notions about mind and brain, and ultimately on notions of subjectivity and individuality. In order to understand the impact of these new maps, I examine in the first instance how maps have developed as both an important feature of experimental practice in functional imaging and a new way for knowledge about mind/brain to circulate. To begin, I will show how maps focus investigations on relations between function and structure in a novel way. These new maps of the mind-in-the-brain arise from the use of new ‘materials’ and tools for research, as well as new research interests in cognitive psychology and neuroscience and new forms of institutional support for this research. A new approach to experimentation will be shown to evolve, as making maps becomes a useful reductionism in the study of function and structure. But reductionism is not diminution, and mapping will be shown to be very productive, as it enables new uses of knowledge about the mind and brain. The mind, once mapped onto the digitalized brain, is in a form that allows it to circulate into the bio-medical sphere. As the mind-in-the-brain becomes a more common object, reconfigured through biologisation and digitalisation, this new object in turn has a particular effect on practices based on traditional mind/brain dichotomies. I will specifically return to these larger issues in the concluding chapter.

Maps and the Structure of Knowledge about the Mind-in-the-Brain

Brain mapping involves relating two entities, rather than “simply imaging”. The need to ground functional data in anatomy was a recurring theme in the development of Talairach as discussed in the last chapter, but mapping is not simply a descriptive task; it is also an experimental strategy. Maps are furthermore themselves tools, technologies for further navigating the mind-in-the-brain, and are used for planning interventions. As discussed in chapter 1, the way representations circulate tie the body to particular systems of knowledge, and connect the individual to particular forms of subjectivity. I will argue here that this is doubly true for the map as representation, since it both structures knowledge in particular ways, linking anatomy and function, and further shapes how brain mapping knowledge is used.

64 I was at first a bit inwardly cynical at all these outpourings of personal stories, in which I recognised the ‘I’ argumentation of certain feminist/post-colonial discussions. (Indeed, upon later analysis, I found that ‘experience’ was a strong overlapping theme between this and certain feminist discussions.) The vehemence of these exchanges made me switch into anthropological mode, however, and led to the insight worked out in this section, about the expanding domain of the brain.
In this section, I discuss the role of geographical maps and maps in general, in order to better highlight the work performed through and with maps in the less familiar context of mapping brains. Maps, by their nature, involve the representation of a territory, and this is probably the feature most associated with maps. Yet, the term ‘map’ has been applied to a number of contexts, from genetics to physics, which are not involved in exploring obviously geographic territories. Hall’s popular book, Mapping the Millennium, points to the following definition as all-inclusive, also applicable to non-geographical endeavours: a map is “a graphic representation of the milieu”\(^6\). Such a definition also applies to brain mapping. Hall also discusses the power of maps, beyond being descriptive. Maps invite possession and interventions; they provide added value to discoveries, through the process of being mapped.\(^6\)

Besides the role of maps as support for knowledge claims, there is a further important relational role embedded in maps, which points to the circulation of the knowledge they carry:

“What maps present is not [necessarily] land possessed but land known in certain respects (Alpers, 1983).”

Maps are indeed rarely simply ‘maps’, or even ‘maps of Amsterdam’ --but rather qualified as public transit maps (with routes, stops and stations), road maps (with one-way streets, parking garages, and numbered highway exits), ‘gay’ maps (with lifestyle appropriate addresses). A purpose is clearly built into the map; maps do not so much record locations as link them to “a living” (Woods, 1993). By studying the relationships that are embedded in maps, and the relationships they further establish by circulating, maps can be analysed beyond their evaluation as accurate or not—a trend in the history of cartography which, it has been argued, could best be replaced by studying maps as part of a system of spatial communication (Wood, 1993; Blakemore and Harley 1980). The representation of a territory, the positing of relationships between territory and a purpose, and a contextual understanding of these purposes should therefore sub tend the analysis of a mapping practice.

A final insight from the study of geographical maps connects the notion of ‘maps’ as representations, to the issues of biologisation and digitalisation addressed in this thesis. A long-standing debate in some geographical circles concerns the factors necessary for the rise of mapping. While some argue for a cognitive basis to its development, in a mode that resembles some old-fashioned explanations for the scientific revolution, others argue that the growth of mapping practices is related to dynamics that further the


\(^6\) Hall gives an example of such ‘added value’, that reminds one of Latour’s argument about the ‘power of inscriptions’ (Latour, 1990). The Norse discovery of North America, which was not accompanied by a credible map, was neither acknowledged nor passed on to subsequent generations (Hall, 1992). This example also seems to constitute a famous ‘case’ in mapping lore.
instrumentalization of social institutions. So while mapping is done by ‘all people’,\textsuperscript{64} map-making is a particular kind of activity that arises in relation to size of a group, the need to integrate people and to keep track of them, and an activity that is related to level of specialisation in a society (Wood, 1993). When the need to keep records grows, map-making becomes an increasingly specialised activity, and systems of representations are developed (Wood, 1993). In this and other chapters (especially Chapter 5), maps of the mind-in-the-brain can therefore be seen to be arising in a context where (digital) record-keeping and the tracing of instrumentalized aspects of health (risk factors, etc) are valued.

\textsuperscript{64} Mapping here is contrasted as a cognitive ability, which can sometimes be given in material form (for example, the native drawing in the sand for the explorer) to map-making, as more formal, not only a material but also an institutional kind of activity.
Brain mappers sometimes jokingly respond to the notion of brain mapping, calling it 'neophrenology' and acknowledging cartography as a 'starting point' in discovering 'how the brain works', and they sometimes reject the label of mapping, because of the implication of one to one relation, I quote at length a fairly typical explanation:

"It partly depends on what you mean by brain mapping. If I understand that you're likely to mean this enterprise of, like mapping the genome, you map the mind, you ascribe function to different parts of the brain or interrelations to different parts of the brain. I mean, what I do can be seen as a project that involves mapping the mind, or brain mapping.....and I'm uneasy, a little bit, about the idea of brain mapping, in that it is very much a cartographer's image, so that there would be a discrete location in the brain for these functions, and it sort of propagates that notion. And it may be that there are no discrete locations and the whole idea of mapping is very imprecise and that the type of maps you get from imaging are very different from the types of maps that you get ...for a walk in the country.

So for example, if I find that there is a city on the map, the city is at those coordinates, I won't expect to find that there is another city there at those coordinates. It's London, it's not Amsterdam, it's not New York. But with the brain, you could have an activation in the front of the brain, say, the task, it seems to be this process that is activated. With another task, you might find with that activation a totally different task. This is two cities in one location. You might say this is the same brain process going on. That is one possibility. The other possibility is a totally different process, but then what that bit of the brain does in terms of that same process is not defined by where is, but by what the other bits of the brain, to which it is currently engaged in cross-talk with.

Like a party phone. You know what a party phone is. It can be a sort of very clear two-way conversation or there could be five six other people all sort of on the same line. I don't know the answer to that and I don't think anyone does, but brain mapping certainly seems to be pitched in the way it's defined anyway, in the first sort of - a city here a city here a city here, to come up with a map... like we have to map the genome (Senior Researcher, trained as psychiatrist)."
The Map as Experimental Metaphor

Definitions and Access to a New Territory

The development of the Talairach system was an important factor in establishing experimental techniques for functional imaging. With the development of conventions for representing the space inside the skull, a framework was built that could accommodate both data about the brain's structure and data about activation that could be detected by PET. A number of techniques for identifying areas of high or low activity in the brain were adopted in research with functional imaging. But beyond the exciting notion of reliably imaging the brain, the common space provided the possibility of articulating and exploring, of mapping function and structure. Common boundaries also played a role in developing localisation research in the 19th century, as analysed by Susan Leigh Star (1989): in correlating findings from neurology, surgery, physiology and pathology, researchers "tacitly agreed on many things, including common boundaries for the phenomena addressed by their lines of work. These boundaries were the skull and the skin." In the case of brain mapping, agreeing on a common space was rather arduous, and anything but tacit.

But besides aligning complex technological and digital measures according to Talairach space, a number of other common elements were developed, which also affected the shape of mapping. Besides a common terrain for measurement, the space inside the skull constituted, in several ways, a new 'material' for researchers, and enabled them to ask new kinds of questions in terms of the 'normal' brain (Volkow and Tancredi, 1992; Roediger, 1995). The 'normal' brain became available for observation, as the focus of PET gradually shifted to research on normal populations rather than clinical cases, as seen in chapter 2. The development of fMRI, considered a less risky technology than CT and PET, which involve radiation, also meant that an even greater part of the normal population could be scanned in functional imaging experiments, and then repeatedly so, over a period of time.65 Children, for example, have notably become participants in brain mapping studies of the normal development of function, while the use of radiation in PET studies would have excluded them on ethical grounds.

Being able to access the normal brain had important implications for a number of approaches to structure/function relations, involving notions of 'normality' of function, greater control in doing experiments and access to a greater range of, or even all, cognitive processes. For neuropsychologists who turned to functional imaging, investigations could take a significantly different shape. It is considered a great advantage to no longer have to rely on 'accidents of nature', where lesions are correlated to dysfunctions through behavioural testing. The ease of working with normal subjects is also frequently compared to the difficulty of working with patients who are ill. As well, granting agencies are sometimes said not to properly appreciate the time-span required to

---

65 The implications of this for 'screening' will become clear later in the chapter.
collect enough data, from the right kind of patient with the right kind of lesion, to be able to complete a piece of research. Having access to the normal brain therefore makes work 'easier', more doable, in some respects. But in terms of the experiments performed, working with 'normal' brains also changes the basic correlation of structure and function. Studies based on the link between a dysfunction and a lesion rely on a logic of deletion (Star, 1989), so that this method identifies essential areas, without which a function is impeded. The particular 'weight' that patient data carries, however, is also acknowledged—it is considered to prove the importance of an area in a way that imaging cannot. This is an appeal to the 'essential' versus 'participatory' role that can be assigned to regions using lesion studies or imaging. Rather than linking dysfunction to an area in the brain, mapping links function and the space of the brain.

Having access to the entire normal brain is also an important factor that shapes brain mapping. The possibility of identifying many areas in relation to function is an important way in which mapping demarcates its work form that of phrenologists, who relied on a 1:1 correlation of organ and faculty (for example, Raichle, 1994a). Again, in contrast to neuropsychology, functional imaging identifies all areas of the brain participating in a function. This is also a contrast between mapping and the work of intra-operative stimulation by neurosurgeons, for example. Other methods for linking function and structure, such as single cell recordings, produced a more 'mosaic' view of the brain. In comparison with these other methods, not only are functions studied in the space of the brain, but this space is that of the whole brain, giving access to entire systems. This is especially highlighted in discussions of the higher functions, which are conceived as being distributed. Higher functions are more complex, involving more areas, and therefore less easily localisable than other motor or sensory functions (I return to this point below). That mapping provides access to this type of complex function may explain why there are many more references to phrenology in the folk histories of brain mappers than to the work of neurosurgeons like Penfield, who concentrated on mapping the sensory and motor functions.66 Brain imaging is also considered to provide a certain 'directness' that was not possible other than in animal experiments--on whom higher functions that are typically human could not be observed. Brain mapping is therefore more direct, in comparison to behavioural testing, but less so in comparison to physiological measurements at the level of neurones, which can only be done in animals and therefore are limited in terms of studying the higher cognitive functions.

The possibility of working with normal brains, of encompassing the entire space of the brain, and of observing higher human functions directly therefore constitute important elements in defining the approach to function/structure correlations in brain mapping. These features of the object of study of mappers are significant in that they highlight features not available to other approaches that aim to link function and

66 By stimulating areas in the brain directly during neuro-surgery, Penfield and Rasmussen (1950) attempted to map the body in the brain, in a motor and sensory version. These maps show a homunculus in the brain, a representation of the body in the brain in sensory and motor versions. See Posner and Raichle (1995) for an example of the traditions in which mappers inscribe their work.
structure, relying on ‘indirect evidence’ of lesions, on the parcellated access to abnormal brains of intra-surgical stimulation, and the limited mental functions of our closest animal relatives (Haxby et al. 1991). The brain maps of the nineties are therefore based on a new full access to this space—a space which encompasses at once and investigates fully, normally, cognitively functional human brain.

New experiments: mapping units of mind onto units of brain

Besides changes in the material basis of structure/function correlations, experimental approaches particular to mapping also developed. These are especially significant in contributing to new disciplinary configurations around brain mapping. Strong disciplinary and institutional divisions have been observed since phrenological research, between those concerned with the understanding of behaviour and those focusing on the structural organisation and physiological functioning of the brain (Young, 1970; Star, 1989). It is useful to describe some of the differences in approaches to studies of function and structure, in order to understand what types of differences in experimental approaches are being bridged by brain mapping. First, while the study of lesions and deficits provides important information about localisation in the brain, the observable symptoms are those that appear in input/output areas. While this approach does link structure and function, this focus on very specific areas is far from the ‘network’ approach of many cognitive scientists interested in function. Thus, “deficit methods [electrical stimulation and clinico-pathological correlations] are not well-suited to prove a concept of distributed cognitive processing (Steinmetz and Seitz, 1991).” Other approaches, within neuropsychology, aim to define functions by looking for mirror deficits, where two patients can be found that show contrasting ability and disability in relation to two functions. These “double dissociations” are sometimes called the ‘golden event’ in the neuropsychological study of patients. In this strategy, functions could be said to be tested against each other, not in relation to (activating) different areas of the brain.

Distinguishing a function, in relation to other functions, is the focus of these psychologists:

“...we should point out that while the dissociations are valuable data it is of no concern to the psychologist where any of these locations are to be found, or how the different locations are distributed in relation to each other (Mehler, Morton, Jusczyk, 1984).”

There is a clear distinction for these authors between on the one hand, the use of patient data for understanding psychological processes and, on the other hand, attempts at mapping psychological processes onto the brain (of which they are very critical). Interestingly, Mehler and many other neuropsychologists have since pursued brain mapping experiments; significant changes in the field have enabled such a rapprochement.

This brief sketch of various methods for studying function and structure provide a context in which to understand the impact and claims of brain mapping using functional
imaging. While other approaches linked function and dysfunction, or function and lesion, brain mapping addresses normal function in terms of normal structure. This indicates new developments because it links objects that had up to the mid-eighties been studied in rather separate contexts—normal (human) function by cognitive scientists and psychologists, and normal (often non-human) brains by physiologists. The next section will show how the relation of functions to structures was made into an experimental strategy.

"The human brain localizes mental operations of the kind posited by cognitive studies (Posner et al, 1988)."

While the normal brain, attractive to those interested in normal function, was becoming more accessible, the possibility of using brain imaging to study the mind became an exciting possibility in the mid- to late eighties. A series of experiments correlated units of mind with (units of) brains, in the shape of a map. Physiological activity, anatomical data and ‘mental’ tasks became linked in the form of maps, as new physical trace of mind were linked to spatial measurements. These were obtained through the subtraction method. While new to PET studies, this method is often traced by researchers to the work of the nineteenth century Dutch physiologist F.C. Donders. Its introduction marked the availability of a physical, mechanically objective trace of mental activity. Historian of psychology Douwe Draaisma describes the original experiments in the 1860s and a second wave of experiments in the 1960s and 1970s. In all cases, the possibility of decomposing and measuring mental activities was at the core of this method.

Draaisma recounts the following about mid-nineteenth century shifts away from a notion of ‘unity’ which was common to the physiological understanding of the nerve impulse and the psychological view of mental processes. Helmholtz’ physiological work established that the speed of the nerve impulse was neither infinite nor that of light, but rather a fast but measurable speed of 100 feet per seconds. Donders, a close friend of Helmholtz, picked up on the possibility of measuring mental processes and developed a method for the measure and contrast of the time span of mental processes. By subtracting the time needed to perform a single task from the time required to perform combined tasks, the duration of each mental operation could be calculated. By the 1890s, a number

---

57 While both neuroscientists and cognitive psychologists by training started taking part in brain mapping experiments in the late eighties, note that these experiments had more of a cognitive psychological flavour. See Figure 1, the icon of mapping studies.

58 A number of historical lines are traced by current practitioners of functional imaging studies. That of physics instruments has been evoked in the last chapter, while the measurement of cognitive activities is traced here. Another line of work is also frequently invoked, pointing to earlier episodes in neurology and neurosurgery (the work of the Italian Mosso and the American Cushing) where blood flow was taken to be a measure of cognitive activity.
of criticisms of this method were published, notably regarding the assumption of 'pure insertion' and interest in this approach decreased.

A second wave of chronometric studies arose in the sixties, and the issue of pure insertion was addressed by Sternberg. He developed a more sophisticated version of the subtraction method, so that the relationship between tasks itself could be investigated, and observed to be independent (purely inserted) or to interact. Draaisma further notes significant differences between the two waves of study, the second reflecting the agenda of cognitive psychology, namely a focus on higher functions, an orientation not only to the duration of the process but also to its nature, a more technical description of processes and the use of converging evidence (Draaisma, 1989). Significantly, data about cognitive activity was obtained through comparisons between the time required for the performance of various functions, or the effects on the amount of time required for performance when certain functions were combined. Sternberg's approach has also been adapted for imaging, so that more relativising comparisons are made between scans than straight subtraction a la Donders. But a comparative approach has remained at the core of subtraction methodology.

Posner, the cognitive psychologist who joined the Raichle group at St Louis, had ample expertise in chronometric methods, and had applied these to the study of attention earlier in his career. Along with Petersen, another psychologist at St Louis, he led the first applications of this experimental approach to imaging studies. The experiments done by Posner and his colleagues retained the notion of a pair of tasks to be performed by the subject. The tasks are selected on the basis of an interesting functional difference—for example, looking at a false font and looking at letters, etc, (see Figure 17).

---

99 This is worth explaining since it is a criticism also levelled against imaging studies. It concerns the relation between the various tasks that are compared: each task is additive, a new process is assumed to be 'purely inserted' on top of a task.
<table>
<thead>
<tr>
<th>Condition</th>
<th>Stimulus Presented</th>
<th>Operation Investigated</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. rest</td>
<td>[eyes closed]</td>
<td>Baseline</td>
</tr>
<tr>
<td>2. fixation</td>
<td>*</td>
<td>visual activation</td>
</tr>
<tr>
<td>3. false font</td>
<td>❄️❄️❄️</td>
<td>pattern recognition</td>
</tr>
<tr>
<td>4. letters</td>
<td>NMHT</td>
<td>letter recognition</td>
</tr>
<tr>
<td>5. non-word</td>
<td>BLOOP</td>
<td>phonological processing</td>
</tr>
<tr>
<td>6. word</td>
<td>BOOK</td>
<td>semantic processing</td>
</tr>
</tbody>
</table>

**Figure 17 Stimuli in a cognitive subtraction experiment**

Each row represents a 'scan' and rows are subtracted from the bottom: condition 2 minus condition 1 = visual activation, etc.

Typical description of an experimental paradigm, adapted and expanded by author.

The scans of each condition are then placed in a standard brain space, and averaged and subtracted (see Figure 18). Statistical tests are run on the data, and the significant activations are taken to represent the localisation of a particular operation in the brain.\(^7\)

\(^7\) For these ‘paradigmatic studies’ see Petersen et al (1988) and Posner et al (1988).
While Posner’s specific participation to these experiments was significant because of his status in the cognitive psychology community, these methods were also well-known to many psychologists who were inspired to apply their own expertise in this kind of design of studies and to collaborate with imaging teams. The impact of these studies has been such that it finds its way into textbook introductions almost immediately in the following glowing terms:

“Only recently have we been able to combine cognitive psychology with brain imaging to visualise the regional substrates of complex behaviours, and to see how these behaviours can be fractionated into simpler mental operations and localised to specific interconnected brain regions. As a result of this convergence, there is a new excitement in neural science today, an excitement that is based on the conviction that the proper conceptual and methodological tools—cognitive science, brain imaging techniques and new anatomical methods—are at last at hand to explore the organ of the mind (Kandel, 1991).”

Units of brain, “regional substrates” could be linked to units of mind, “simpler mental operations” by being visualised. This was a “convergence” of mind and brain. A research agenda was therefore emerged, as were neologisms to describe it. Mental processes are to be mapped:
"uniquely human functions must be assigned to networks of brain areas; cognitive processes require definition in physiological and anatomical terms (Frackowiak, 1998b)."

Mapping operations onto structures, assigning functions to networks of brain areas constitutes an important experimental strategy which has acquired the status of paradigm in brain mapping research. Since 1988, this method has been adapted and data analysis packages developed, but the aspects described here are paradigmatic for activations studies. Furthermore, while developed for PET experiments, this approach has largely been adopted for use in fMRI studies.

**From Processes of Mind to Patterns in the Brain**

The description of the origin of this method is not only interesting in itself, or because of the intriguing dynamics of experimentation at which it hints, but this story also highlights an important shift in the methodology when linked to imaging. This shift has important consequences for the kind of object produced by this research. Significantly, when used in functional imaging, the subtraction methodology involves recasting the measures of difference between cognitive tasks from time to space. The 'trace' that is elicited from the mental phenomena is neither its course over time (Donders, Wundt), nor its relative effect on the performance of tasks (Sternberg paradigm), but its presence in space— in the space of the brain. This method links mental function and physiological activity, putting the mind in the space of the brain, in what has been called a "joint anatomical and cognitive approach" (Posner et al, 1988). It is also an approach that accommodates the notion of systems, which are key concepts in cognitive science and the current theories of higher cognitive functions. If a system is broken down into components in a psychological model, then the existence of its various components can be tested, since they will produce different patterns of activation: "differences in the

---

1. The notion of hierarchies of functions also affects the design of experiments: the more complex the task, the more arduous the experimental design since complex tasks cannot be as easily broken down:

   "One difficulty with many imaging studies of language is the choice of complex tasks involving multiple functions that, along with the lack of appropriate control conditions, preclude the ability to tease apart precise structure-function relations. (Haxby et al. 1991)."

This therefore calls for complex subtractions, which will compare complex tasks:

   "In all cases, the experiments rely on contrasting the distribution of brain activity under different conditions, but whilst the initial studies relied entirely on simple cognitive subtraction, experimental designs have subsequently been elaborated to include factorial designs, parametric designs, etc (Price, 1997)."

2. Star (1989) notes that localisationists were often taken to task for not having a theory of how mind and neural activity are linked, relying on temporal simultaneity to associate these events. Similar criticisms are also made about brain mapping, where experiments are said to show correlation but not causation. See 'Peer Responses' to Posner and Raichle (1995). See also note 76.
distribution of perfusion between brain states [is used] to identify areas associated with the components of specific tasks (Frackowiak, 1994). It is in this sense that mapping inscribes the mind into the brain at a systems level, with the highest functions within reach.

Furthermore, this new experimental strategy points to what has been the dominant 'unit' of knowledge in brain mapping: subtractions. When scans of different tasks are subtracted, the areas in the brain that are seen to be active in the image of difference can be linked to the difference between the tasks (see Figure 17). Rather than imaging the function in the brain specifically, the image is obtained by comparisons of tasks: "subtractions associate a specific cognitive process with sets of brain regions" (Cabeza and Nyberg, 1997). Subtractions therefore structure knowledge about the mind-in-the-brain that is produced in these experiments. When authors review brain mapping articles, they do so in terms of subtractions, and when brain mapping results are incorporated into databases, it is also in terms of the locations of subtractions. With each localisation representing a component of a task, maps in this endeavour therefore relate cognitive operations in the brain, bringing together spatial traces of cognition and spatial traces of anatomy. Mapping brings together notions of functions from cognitive psychology, while localisation in the brain links this work to neuropsychology and neurophysiology.

The terrain of the brain becomes available for mapping and subtraction provides an experimental strategy for linking structure and function. This space is established as an important basis to explain cognition, to explore the brain as the foundation of mind.

73 There is a debate about whether psychological functions should be sought in the brain or whether activation should dictate what are separate functions. This approach relied on the fact that visual areas, along with other components of perception and sensation are considered localisable to a greater degree than for other ('higher') functions:

"In contrast to these higher-order areas, primary cortices show robust PET signal increases during specific functional activation... Also, primary areas have been shown to display little variability of functional organisation (Steinmetz and Seitz, 1991)."

Work on vision and attention is also considered to be more encouraging than on language processing, again, because of the hierarchical understanding of functions and their complexity in relation to networks, the argument being that "neuromaging studies of language should connect with psycho/linguistic theories" because of the degree of complexity of this function (Poeppel and Johnson, 1995; Pinker, 1994).

74 For example, "BrainMap relates brain locations to human behaviours and data sources. For any brain region, the behavioural conditions believed to support that behaviour can be retrieved. BrainMap data naturally falls into a hierarchical structure. The highest level is the paper. Each paper is divided into one or more experiments. An experiment is a grouping, typically a pairing, of behavioural tasks for which differentially activated locations are reported. Behavioural conditions identify the particular effects for which each experiment was designed. Methodological details such as modality and tracer are also provided for each experiment. Each experiment includes one or more activated locations. Locations are the lowest, most basic level of the BrainMap hierarchy. All information within a paper is linked throughout the hierarchy, providing ease of access up and down the branches of the hierarchy (http://ricatbseca.edu/services/brainmap_paper.html)."
Where Tells You What, or Maps as Arguments about the Nature of Mind

What is the nature of thought? Do we think in “words”? In “propositions”? In “pictures”? Such questions can be addressed as part of the new agenda for exploring mind and brain, through the production of a map. Functional brain imaging has given a new direction to a long-standing debate surrounding mental imagery. The nature of mental imagery was investigated in cognitive psychology as a debate about mental representations (Farah, 1988; Kosslyn, 1980; Pylyshyn, 1981). Representations, in the sense of mental objects, are a key concept in cognitive science, and marked the shift of cognitive science away from behavioural psychology (Paivio, 1969). Stephen Kosslyn, professor of psychology at Harvard, and one of the cognitive scientists to have explicitly made the move to cognitive neuroscience (see below), had been involved through the seventies and eighties in a debate concerning the structure of the mental representations underlying the experience of mental imagery. Kosslyn argued that these representations were actually quasi-pictures (Kosslyn, 1994). Another main participant in this debate, Pylyshyn, argued that the mental representations underlying mental imagery were ‘propositional’, and similar to linguistic representations.

The debate went on, says Kosslyn, because “the theories were too unconstrained”. Too unconstrained when discussed in cognitive science terms, that is. As neuroscientific data was brought to bear on the debate—not only alongside cognitive data, but as determinant or foundational to cognitive data—a further turn was taken in the study of the mind. Neuroscientific data provided

“a way to ground this research, to remove some of the degrees of freedom that made it so easy to explain the results (Kosslyn, 1994).”

“Degrees of freedom” were removed by recasting the question from one addressing the kind of function involved in mental imagery, and instead posing the question of the nature of this function in terms of how it would map onto the brain. Aiming to solve the imagery debate, Kosslyn, Nat Alpert and colleagues at the Massachusetts General Hospital PET group developed an experiment to study mental imagery as a localisable function:

“If one wants to know whether two tasks rely on the same processing, then showing that the same patterns of brain activation occurs during both can help one answer that question. If one wants to know whether two processes are the same or different, then finding separate patterns of activations can answer the question…. Given that the area is activated, one has evidence that a specific process is used to perform the task (Kosslyn, 1994).”

Faas also argues in his analysis of the debate from its post-behaviourist revival in the seventies up to the late eighties that the issue as addressed by Pylyshyn and Kosslyn is underdetermined. He proposes a turn to connectionist explanations as a way out of the impasse (Faas, 1993). The brain, however, becomes the constraining element in subsequent episodes of the debate.
The experiment found that parts of the visual cortex were activated when subjects mentally form visual images (Kosslyn et al. 1993). From this experiment, the authors argued, mental imagery could be considered to be 'visual', since it involved activity in the visual areas, and produced a pattern of activation in the space of the brain that differed from those involved in linguistic processing. Other studies have found different activations, and the point here is not to argue for progress in this debate—but to show its development as a result of the involvement of functional mapping approaches, which recast the debate from a functional level to the level of the mind-in-the-brain.

This way of arguing is a significant development, one in which neural substrates are linked to functions through brain mapping, and are brought to bear on psychological concepts. Not only are functions localised in the brain, but those localisations themselves become evidence for positing relations between functions. Reviewing the results of imaging studies of mental imagery, these authors restate the results, insisting on the common substrates of function in the brain, as a way of understanding cognitive processes:

“Consistent with the idea that imagery and perception have common neural substrates, imagery subtractions have yielded activations in occipital regions (Cabeza and Nyberg, 1997).”

In this approach, knowing where a function is located informs about its nature: the relations posited in the map speak to the way the mind works. This new way of arguing using maps is typically formulated as follows: when more than one cognitive model can explain the observed behavioural data (time or response accuracy), there is a need to look for further ways of constraining models. In other words, by linking the definition of functions to brain areas, the brain can be used to test the mind.

Mapping experiments therefore have further important consequences for theories of how thought is supported by the brain. By identifying patterns of activation in the brain with various tasks, cognitive tasks themselves can be redefined. These arguments often involve hierarchies of tasks, from the simpler sensory localisations to more complex mental ones. Visual thoughts can be shown to involve visual areas:

“These findings support the general idea that processes initiated internally from instructions ['purely mental'] can activate the same sensory areas where these computations are performed on actual sensory evidence [external stimuli] (Posner, 1993).”

76 "Support", "substrates", "correlates", all terms used to point to, rather than define, the relationship between the mental and the physical—a long standing strategy to avoid the complexities of pinning down this relationship. For other examples of the use of such terms, see Smith (1999) on representation in the first part of the twentieth century and Star (1989) for a number of terms used in the latter apart of the nineteenth century, notably Jackson's use of "representation".
The principle developing here is the association of ‘perception’ areas with higher function areas in the production of higher cognitive functions (attention, imagination, memory). Furthermore, in the study of higher functions, if visual thoughts involve visual areas similar to activations during visual perception, how does one distinguish between them? Again, associations of space and function are part of the answer:

“If these states are to be distinguishable, then they must be associated with different patterns of brain activity. We propose that this distinction critically depends upon frontal activity, and in particular, on the relationships between frontal activity and activity in the location that determines the contents of consciousness (Frith and Dolan, 1998).

The contents of mind are therefore dependent on the relationship between activated areas. From mapping the patterns of cognitive activity, the nature of higher functions can be known through patterns in the brain. While there are some minor variations, many streams of investigation in brain mapping have followed this logic, trying to elicit different patterns in the brain in relation to functions. Some investigators have also explored subtle differences between the performance of higher functions. The study of memory and its accuracy is one such area, where researchers have investigated the possibility of predicting patterns of activity as indicative of accurate or inaccurate recall.”

Brain imaging has been said to introduce the ‘where’ question in cognitive psychology (Raichle, 1998), an issue which had not been of concern and often dismissed in favour of an independent psychological level of description. ‘Where is there activity in the brain?’ is therefore becoming part of the strategy for understanding the mind. Functional imaging is argued to be the privileged tool to perform these tests (Cabeza and Nyberg, 1997), and is often explicitly named as the cause for the shift to the brain in cognitive science (Solso, 1997). More than a new technology was needed, however, to introduce this question. An experimental strategy had to be developed to relate the interests of cognitive science to the brain.

There are also implications at the disciplinary level of these changes in experimental practice. The arising tensions can also be understood in terms of mapping. The primacy of the ‘cognitive level’ in current mapping experiments has been criticised in terms of the dominance of approaches where the mind is mapped onto the brain. In order to identify functions in the brain, there has to be a pre-existing model, with which to design tasks and order subtractions:

“PET technology can only be used after the psychological processes whose brain bases we want to explore have already been worked out, or at least we have an

---

adequate working model for them. PET technology can only be applied to unravelling the neural processes once the underlying psychological processes have been adequately specified (O’Mara, 1995)."

Other non-cognitive psychologists have made this argument even more strongly, and argued that this need for a priori models is the result of the dominance of cognitive psychologists (and of their approach) in designing brain mapping experiments (Shulman, 1996; Friston, 1997). If cognitive psychologists have remade the mind in terms of its being mappable in the brain, a priori models are needed in order to select contrasting tasks. This practice receives the following warning: “We must avoid the false sense of security of believing that we have succeeded in carving nature at the joints: patterns of activation are not simple by-products of brain tissue but depend on how we have conceptualised the problem (Paller, 1995).”

Making maps indeed implies the reconfiguring of certain concepts in the study of the mind. These tensions also become visible around the map. The notion of network is best explored in terms of time, in terms of flow. As we have seen, space, structure and anatomy become the organising elements in these experiments. When linked to maps, some aspects of ‘networks’ must be adjusted while others are minimised by the mapping methodology. When cognitive scientists translate their research into brain mapping terms, the flow diagrams they posit are shown in the brain, but “all at once”. Similarly, while neurophysiologists may now be exploring the whole, normal human brain, they must also compromise the element of time, which they have traditionally investigated with electrodes. Arguably, PET does trace function over time (flow) but it does so over a period of some 40 seconds, and scans show all activity during this period (rather like an old fashioned photography with long ‘exposure time’), and this order of magnitude is not comparable with the millisecond measurements of neurophysiology.

There have been major efforts to reduce the compromise that must be made in order to obtain data through brain mapping, while maintaining the advantages it brings. Much research has gone into adapting the time resolution of fMRI to enable it to trace activity through the network. As well, other technologies with better temporal resolution have been embraced as part of the armamentarium of brain mapping. This can be described as an effort to recover ‘time’ in the study of cognitive process and brain activity.

\[86\]

---

\[78\] The prevalence of this objection was brought to my attention by Joe Dumit. It has many implications, indeed. If mapping allows cognitive psychologists to ‘see where their boxes are’ (see chapter 4), all the boxes appear at once. This loss of the time dimension involves the blurring of the distinction between serial and parallel notions of organisation of brain (Volkow and Tancredi, 1992). There have been attempts to recover this dimension by using other technologies to investigate and to integrate a notion of effective connectivity in imaging studies (See for example, Wagner, Shacter et al, 1998; Buechel, Colli and Friston, 1999).
A Mapping Practice and a Map-making Community

While Star concludes, in the late eighties, that the streams of research that address the mind and those that address the brain are too institutionally segregated to really produce an integrated view of the brain, these institutional boundaries seem to be redrawn and blurred as PET research groups develop methodologies that cross these divides. Cognitive neuroscience is a label often used for this emerging stream and is defined as the joining of cognitive science with neuroscience. Researchers, many from cognitive science, have chosen to use neurobiology, (or more broadly, what is known about the brain) to constrain models of function or to establish the “cogency” of theories of higher brain function with what is known about the brain (Mulder et al. 1995; Frackowiak, 1994). The first editorial of the new Journal of Cognitive Neuroscience stated that

"Those cognitive scientists interested in a deeper understanding of how the human mind works now believe that it is maximally fruitful to propose models of cognitive processes that can be assessed in neurobiologic terms. Likewise it is no longer useful for neuroscientists to propose brain mechanisms underlying psychological processes without actually coming to grips with the complexities of psychological processes involved in any particular mental capacity being examined (Gazzaniga, 1989).”

While the localisationist legacy involved separate institutional structures dedicated to mind and brain (Star, 1989), the new mapping approach points to a reconfiguration of these segmented fields.

Maps of the mind-in-the-brain have been said to provide a new level of concreteness to theories of the brain and mind, and images of brains in action have proved to be fascinating to a number of audiences. But while the beauty/esthetic appeal of these images is not negligible, the descriptive aspect of maps is only one of its functions. Maps serve a relational function, organising experiments in terms of space and function.

The shift to the space of the brain has been attributed to changing notions of function in neuroscience, notably the decrease of the dominance of the understanding of function to an electrical definition (itself associated with the technology of the EEG). Others have pointed to the convergence of imaging technology with theoretical

---

79 The instances were rainbow images of the brain are used, often colour enhanced MRI or PET scans, are too numerous to list here, and would form an interesting separate study. Notable among these are the circulation of the ‘Hearing words, seeing words’ images. Countless psychology, neurology and neuroscience textbooks also feature brain scans on their covers, while brain imaging per se may form only a small part of their contents, pointing to an iconic or emblematic role of these representations which stand for thought or mind.
developments in cognitive science, and the availability of theories positing the right kind of model, with an appropriate type of 'units' of cognition (Raichle, 1998).

Others stress a different change in the theoretical landscape, one which points to a growing shift towards material bases for cognition: as models in cognitive psychology become less metaphorical, reduction to firm foundation seems desirable. (Roediger, 1997). I will comment on this later, but note for now that past revivals of subtraction methods may also be indicative of some of the dynamics that lead to the popularity of subtraction. These episodes seem to mark periods in time where the 'mind' is hailed as within reach of scientific exploration, and to be closely tied to sets of technologies which ensure the mechanical objectivity of these measurements of the mind. These episodes of "cognitive subtraction" also seem to mark disciplinary changes, linked to changing types of empirics. While this issue cannot be explored at length here, interesting points of comparison might be found in the parting of physiology and psychology with Wundt's work, the growth of cognitive science in which the Sternberg work develops, and in the case of brain mapping, a closer association of psychology with physiological research. The investigation of mental processes as building blocks also seems to link these various research efforts, though as I analyse here, the mind is shown in the earlier cases to have a physical dimension in time, while the brain mapping studies tend to highlight the spatial dimension. The work leading up to these experiments discussed in this and the previous chapter also point to other significant factors, namely the material organisation of research, both in terms of the use of normal brains and in the formation of a digital context for these experiments.

These representations serve to relate units of anatomy and cognition, and can be seen to support changes in experimental practises, and disciplinary boundaries and aspirations. This turn in cognitive science has been called “wet mind”, evoking the physical component of this kind of cognitive research. The dryness of cognitive

---

80 Chapter four contains a discussion of the contrasting kinds of evidence of those working in time and those working in 'all four dimensions'.

81 While the notion of directness is discussed here mostly in terms of penetrating the skull, in contrast to relying on behavioural measures, a less frequent but fascinating and recurrent theme has to do with defining the directness of imaging through its bypassing of experience, in favour, again, of a material basis for explanation. I quote briefly from different authors to give an idea of how this argument is made:

"Subjective response of volition, pain etc, while difficult to quantitate and understand, are caused by brain activity just as are the responses currently postulated in cognitive neuroscience. An opportunity for treating the brain organically is offered by functional imaging, whose response does not reflect the observer's understanding, but directly shows brain activity (Shulman, 1996).

This theme of the opposition between objective measurement and phenomenological understanding is found at the beginning of these studies in the seventies: "the wider the cognitive unconscious, the greater the scope of the chronometer (Draaisma, 1989)." This form of directness which bypasses experience in favour of a material basis, remains a common trope in presenting them: "We experience mental processes as essentially instantaneous smooth operations" but these can actually be broken down into operations and imaged (Kandel, 1991).

psychology flow charts, behavioural measures and computer modelling are contrasted with the wetness of newly available biological data, the flow of blood in the brain. The wetness of the living mind, however, is apprehended through its encounters with the thoroughly digitised brain. The physical mind of subtraction experiments meets the virtual brain of the Talairach system.

Expanding the Territory: Effects on the Mind Become Effects on the Brain

La notion d’habitus, telle que nous la propose Bourdieu fait partie selon moi des “concepts passerelles” (et pas seulement des mots passerelles) potentiellement utiles dans les divers disciplines qu’il réunit. Le concept lie la notion d’apprentissage à celle d’empreinte de l’environnement social et culturel, très précisément dans le contexte des représentations sociales dont nous parlons… Il est donc urgent de développer la recherche sur l’inscription neuronale des représentations sociales et en particulier, des représentations éthiques de soi et des autres (Ricoeur et Changeux, 1998).

Mapping has also further extended the range of phenomena that are to be measured in the brain. If aspects of mind can be traced in the brain, the possible ‘forces’ that affect these aspects of mind have also been mapped in the brain. This means that development, environment and experience or expertise, can also be traced in maps of the brain and made visible by the brain scanning technologies. These maps are like geological views of the brain, showing how learning and environment have left their ‘imprint’ on the brain, as Jean-Pierre Changeux, a prominent neuroscientist, indicates in the quotation above. The process of biologisation of mind is therefore productive of new relation between measurable differences in the brain and the elements that shape the mind.

Scans of Youth

The experiments described in the opening of this chapter constitute such a mapping of development. In this research, not only is function mapped to places in the brain, but the issue of how a function would even come to be located in a given place is investigated. Bilingualism and language-specific activations have been the focus of many such studies. The mapping logic redefine these activities in terms of their systematic localisation, (or lack thereof), in the brain, as a way of understanding these developmental processes in terms of the structure-function relationships in the brain. For example, the effort required to speak a second language comes to be redefined as supplementary ‘extra’ activation or atypical activity in the brain. Research on bilinguals, for example, has found that even in very early bilinguals, some ‘extra’ activations were involved: the left putamen, believed to be involved in producing rote movements, was active in the second language (Klein et al, 1995; Barinaga, 1995). Such redefinitions of language learning processes in terms of the brain have important implications. For example, brain mapping
studies of brains of people who stutter found differences in activations between speech during ‘chorus reading’ where they did not stutter and when they did. These results analysed stuttering at a systems level, and suggested that it might be linked to a general flaw in language development, that lends support to a new view that speech therapy should begin as soon as a child shows signs of stuttering or lack of fluency, often as early as age four. Treating the problem early, when the language system is still malleable, should offer the best chances of actually influencing language development (Barinaga, 1995).”

The relation of function and structure can therefore be investigated as to the effect of development on this relation, and this also for the ‘higher cognitive functions’. Bilingualism and language acquisition are certainly complex phenomena, and here, their cultural components are translated into measurable biological difference.

Language is not the only activity where development is considered significant and investigated in the brain. The following excerpt of a review of neuroimaging in the developmental disorders describes the new agenda:

“The developmental disorders of childhood—autistic, developmental language, reading (dyslexia), and attention-hyperactivity disorders—manifest with deficits in the traditional behavioural domains of cognition, language, visual-spatial function, attention, and socialisation. ...Developmental cognitive neuroscientists must therefore begin with the spectrum of sometimes divergent behaviours occurring within these disorders and work backwards in an attempt to identify the responsible anomalous neural systems, ...current neuroimaging techniques give us the technology for the first time to apply a fundamental cognitive approach to brain-behaviour relationships in the developmental disorders... (Filipek, 1999)”

The line of argument pursued here is familiar: it is now possible to explore cognition in the brain, thanks to imaging technologies—and as we have seen, a number of shifts in experimental strategies and disciplinary collaborations. As in the studies of normal function, functional imaging provides studies of development with the promise of touching the hard core, the brain-based anomalies that might clarify these childhood disorders. These examples begin to make clear how shifts in mind/brain definitions in research are related to other spheres that rely on such definitions. As development is increasingly understood as the way the mind comes to be mapped on the brain, so interventions in development (whether normal or requiring therapy) also focus on the mind-in-the-brain basis of development.
Scans of Experience

Besides development, other types of traces of experience and expertise are also being sought in the brain. Following the language studies of the late eighties, Posner explored experience as found in the brain.

Figure 19 The brain of subjects performing a task as new, practiced, and novel.

A novel task does not require as much effort as a new task—the brain's learning of new skills and their application to novel cases are taken to be shown by this experiment. Note that the colour scheme is reversed; here, lighter colours indicate a larger decrease in activity.

In the experiment being referred to here, a different pattern of activation was visible when subjects performed a word-generation task. In a 'naive' condition, scans were made as subjects performed the task for the first time. Another series of scans were made after subject had been practising with a given set of words for 15 minutes. When a novel set of words (new words, same practised task) was introduced, the activation was not as great as it had been in the naive condition—some learning had occurred and was carried over into this new condition. Posner reflected on these experiments:

“If the neural systems used for a given task can change with 15 minutes of practice as in the figure, how can we any longer separate organic structures from their experience in the organism’s history? We must be able to trace the changes in the brain that occur with experience (Posner, 1993).” Experience is therefore fully traceable as a factor of the brain’s activity.

Other types of expertise are also being imaged, based on the skills of subjects—musicians’ pitch discrimination, cab drivers’ spatial memory. Patterns of activation here show not only the performance of a task (“experience”) but are taken to give information on the changing performance of the task or the abilities some types of subjects have developed for recognising perfect pitch or remembering routes (“expertise”).
Another (perhaps more phenomenological) way in which experience is being mapped, relies on a similar logic as the imagery experiments described above. This mapping involves relating the localisation of words with the way the entities they represent might be bodily encountered. Different sites might be found for different categories of words because of the

"overall physical characteristics of the entity being named, which determine the sort of sensorimotor mapping generated during interactions between an organism and the entity, and which are key to the neural mapping of corresponding conceptual knowledge (Damasio et al. 1996)."

Following this argument, we all know tools in similar ways because our bodies interact with these objects in common ways, which, in turn contrast with interactions with "non-manipulable" animals (Damasio et al. 1996). This is a view of the mind-in-the-brain that considers learning as constitutive of cognitive abilities, which is not so revolutionary in and of itself. But insofar as learning and learning contexts are treated as factors affecting mapped relations, this research takes mapping to a new level, linking it to expertise and experience. These too become features of maps.

**Scans of Culture (Naturalised)**

In a similar vein, the issue of nature/nurture has largely been pronounced dead—we now know it is both, and "simply" a question of degree, rather than of the determinant role of one or the other. Nurture (environmental influences) has also been analysed as a factor affecting function in the brain. Child abuse, (which here is defined as the lack of nurture) can also be mapped in the brain. In one striking case that was widely covered in the popular press, the brain of a Romanian orphan, deprived of care, is contrasted with that of a healthy child, and the lack of activation is linked to a lack of emotional/cognitive abilities (Chugani, in Begley, 1996). The study of child development, the rearticulation of a proper environment in terms of effects on a biological, measurable traces has grown tremendously in the nineties, partly in relation to the availability of fMRI.

---

This analysis begs the question of just how the experimenters assess (or assume...) how much exposure to LIVE but non-manipulable animals these subjects received (as opposed to learning about cows from stuffed toys, television and picture books) and whether experience really can be so pure as to be divisible in this way. Would it follow that my young nieces, acquiring language on a farm, are localising the notion of cow with that of tractor, exposed as they must be to the manipulations of these animals in the context of modern techno-agriculture? Do their brains differ from those of the neighbours’ children whose farm experience might not involve these techniques? I am also intrigued by the possible implications of this analysis for teaching and knowledge transmission: might we know some concepts more abstractly because our experience of them is more abstract? And what does this mean for notions of tacit knowledge and the difficulty of transmitting it abstractly or formally? In spite of my initial sceptical reaction, Damasio et al’s reasoning might be interpreted as making a case for an anthropological turn in cognitive neuroscience.

---

A number of events, articles in the popular press and books have fostered the incorporation of neuroscience in discussions of child development in the course of the Decade of the Brain — for examples of relations between neuroscience and development, educational policy, ‘family’ policy, and parenting advice, see Chugani, 1998; Gopnik et al. 1999; Bruer, 1999.
Yet, while a new relation between nature/nurture has been announced as a reconciliation, it is not a conversation of equals. The methods used to measure the 'nurture' component come from the 'nature' armamentarium.

"Psychiatry is at a cross-roads. The relative advantages of pharmacotherapy versus psychotherapy are subject to rivalrous debate. Genetic studies are being challenged by studies of social factors in mental illness. These debates are typically framed as biology versus environment, nature versus nurture. What is lost in this debate is that the substratum for pharmacotherapy is identical with that of psychotherapy: both act on the brain. Similarly, genetic and social factors both produce their distinctive actions by altering neural processing of information in the brain. NIMH research is creating a new foundation for psychiatry and the treatment of mental illness by revealing the same valid biological contexts for psychotherapeutic approaches and pharmacotherapies (Koslow, 1995)[emphasis added]."

Nurture also counts, but only once translated into a measurable activation, in the biological terms of the brain, as differentiated activation. Biologisation of mind in brain mapping does not ignore the social or the environmental, on the contrary, it takes it rather seriously, and renders it as a feature of the map. The relational role of the map is therefore a complex construction of links between mind and brain, in experimental work and in interdisciplinary relations.

Navigating by Maps

The map as experimental metaphor constitutes one level of the function of maps: maps also link territories, readers and systems relevant to territories. In Wood's terms, a map links readers to the world the map embodies, and other aspects of vast systems—codes, laws, or agreements having to do with ownership in the case of property maps (Woods, 1992). The same dynamics can be fruitfully applied to these biological maps: the readers of the maps, and the owners of mapped territories are linked through the map to biomedical systems of diagnostics and intervention. These maps are also involved in systems of screening, an area which has been increasingly prioritised in both the health care sector and bio-medical research. Furthermore, by representing mind and brain as

---

85 Other notions which are being constructed as 'factors' will return in other chapters. For example, individuality is based in one's mind (as opposed to one's soul). But if the mind is the brain in action, then one's individuality becomes inscribed in one's brain. The particular dilemmas posed by this issues and extreme amount of attention devoted to differences between individual brains will be addressed in chapter 5.

86 Of 5 priority areas at the American NHS due to receive central funding, screening and studies of populations figure on the agenda as the need for "methodology to establish mental health needs of a particular population. The British Medical Research Council's policy relevant to neuroscience has four aims: the exploration of the relations of culture, biology, and psychology, investigation of the effect on
overlapping) features of a territory, these maps of the mind-in-the-brain bring together previously separate systems which dealt with either mind or brain. These maps link social, psychological and environmental factors to the biological structure of the brain. The reach of mapping studies extends into the examination of notions of the self, in the sense of one’s potential and of one’s biography. As these notions are mapped in terms of the space of the brain, they also enter brain-based systems for establishing normality and pathology.

The long tradition of the use of mapping in neurosurgery might make this area seem obviously suitable for the clinical application of functional brain mapping. Pre-surgical mapping is indeed one of the most widely recognised ‘applications’ of brain mapping. A component of the Human Brain Project also aims to combine intra-surgical and cognitive mapping. The organising principle in these maps, however, is the identification of essential ‘naming’ sites. A surgeon’s goal is identify essential sites, so as to refrain from removing them (Brinkley et al, 1997), and this clearly contrasts with the identification of networks of distributed areas as investigated in brain mapping, for example in Petersen and Posner’s work discussed earlier. Surgeons seek to identify this essential area because interfering with brain tissue too close to ‘naming’ areas causes deficits, and all aphasias include naming difficulties (Brinkley et al, 1997). In this logic, the area is the key to the naming function, and naming dysfunction is the key to aphasia. There is therefore some distance that has not yet been entirely bridged between the more localisationist focus of neurosurgeons and the distributed maps of cognitive neuroscientists—the mapping project is considered valuable for assisting in the stimulation task, but would not replace it (Brinkley et al, 1997). Others have been more enthusiastic, especially in paediatric neurology, where radical surgery for intractable epilepsy has been performed on babies and young children based on surgical ‘road’ maps (Chugani et al, 1987).

The strength of this traditional approach to epilepsy and tumour neurosurgery does not mean that functional brain mapping’s focus on systems and networks is incompatible with surgical intervention. Suggestions have been made for neurosurgical interventions based not on the avoidance of a targeted point, as identified by electrical stimulation maps, but on the mapping of a misconnection. Neurosurgery of the mind-in-the-brain therefore involves intervening in the system, rather than excising the localised cause of pathology. Thus, in relation to the particularity of these maps in showing the systems’ level, the notion of “systems neurosurgery” has been suggested. Surgical interventions would then be planned in relation to a mapped system in the brain, for conditions such as stuttering or post-traumatic stress disorder (Motluk, 1997).

biology and function of genotype and social environment, and fourth, the development of ways of applying these findings clinically (Seemungal et al, 1999).

87 This procedure was first reimbursed by Blue Cross in the early nineties (Hoffman, 1993).
88 This atlas is being developed so as to produce probabilistic data, as will be explored in the next chapter: “Once a sufficient number of patients have been entered in the database, we will be able to generate probability maps of likely language sites, based on patient characteristics such as age, gender and verbal IQ (Brinkley et al, 1997).”
There have been suggestions that brain scans could be used for differential diagnosis, between dementia and Alzheimer’s (Duara et al., 1999), or to rule out certain forms of mental illness (Kevles, 1997), including schizophrenia (Dumit, 1997). Applications of brain mapping in the field of rehabilitation have also been suggested, based on the notion of the brain as flexible networks. Between equipotentiality and the strict localisation of functions, this approach assumes a (limited) possible reorganisation of networks in the brain. Rather than focusing on limiting local damage on the one hand (the neurologist’s task) or teaching a skill anew (in traditional rehabilitation), treating a patient after stroke could also be based on an evaluation of mapped dysfunctions. Strategies for treatment could then be evaluated on the ability of a system to rewire itself, to take an alternate route and shape therapies to help people recover after strokes.89

In terms of mental illness, a link with the brain has been established through functional mapping technologies. While the knowledge of a link between neural abnormalities and mental illness is over a 100 years old, the argument goes, now “brain imaging techniques make it possible to identify the anatomic, metabolic and neurochemical substrates of mental illness (Andreassen, 1988).” In this version of mental illness in the brain, distributed function, a key element as we have seen in functional brain mapping, is also prominent: “eventually, all these types of symptoms must be understood in terms of the interaction of neural systems and neural circuits (Andreassen, 1988).” Indeed, this has become the dominant direction of mapping studies of mental illness:

“It is becoming increasingly evident that a lesion model is inappropriate and that a more relevant characterisation will be found in terms of disorders of functional interconnections between brain regions (Frith and Dolan, 1998).”

Brain mapping has explored the ‘routes of information’ between brain regions implicated in schizophrenia, identifying the “functional circuitry of the largely unchartered domains of psychosis (Buschbaum, 1995).” A recent study used scan-based measurements of the development of pathways in the brains of children to evaluate normal maturation of the brain. This research further pointed to the possibility of investigating the lack of such development:

"Our findings may also provide guidance for future investigations of neurodevelopmental disorders such as schizophrenia; the abnormal rate of myelination during childhood may very well underlie the emergence of psychotic symptomatology (Paus et al. 1999).”

89 In the middle of the 20th century, when localisation represented a stricter relationship between areas and functions, plasticity had been an argument for leaving behind the concepts of localisation in a clinical context (Harrington, 1987). Here, the possibility of recovery, the plasticity of the brain, is reconciled with localisationism, through the notion of function as a network—a network which might reorganize and recruit different nodes after injury.
These analyses are based on pipeline-type analyses, and clearly open up the possibility of screening in an 'at-risk' or even non-symptomatic population.

Besides screening for mental illness, another type of application of mapping would be to use brain mapping techniques to evaluate mental representations. Activations that are typical of learning disabilities (for example dyslexia) could also be mapped and serve ‘screening’ or diagnostic purposes (Posner, 1997). Building on the kind of work described around the mental imagery debate, it might be possible to tell whether mental representation are the result of memory, imagination, or perception, based on the relation of the activation of the sensory and the motor cortex. These applications therefore introduce the possibility of making brain maps and brain scanning into normative approaches, where mental processes (and not ‘simply’ outcomes) might be subject to evaluation, a use that has already been considered for phenomena as diverse as false memory and ADHD.\(^{90}\)

These various examples show how the mind is brought into systems of clinical intervention and (epidemiological) population management through its being mapped onto the brain. Some of the tools and applications are further discussed in the next chapter.

**Brain Maps and Gene Maps**

Brain mapping has also explicitly been aligned to a genetic understanding of the brain’s potential. Maps of brain activations are then posited as complementary descriptions of biological entities. Specifically, whereas genetics will inform about the genotype, scanning the brain provides access to phenotype:

> “Individual genetic makeup and learning together shape brain structure. We now have methods to understand how this takes place and what it means for the limits of human potential (Posner, 1993).”\(^{91}\)

Again, we see how potential and expression, nature and nurture, are defined in biological terms, and associated with different mapping methods that can evaluate these. Note also how brain structures are the meaningful elements—the relation of structure and function is assumed to follow, the brain being the solid foundation of human (mental) potential. Again, this approach is being applied not only to function but also to dysfunction:

---

\(^{90}\) For example, Michael Posner, when asked around 1995 to imagine the table of contents of the *Journal of Cognitive Neuroscience* in a Decade (2005), listed among other likely titles: “How communication between brain areas involved in first and second language comprehension change with mastery of the new language.” No more oral tests in the language lab with earphones and tapes: a brain scan will define your level of proficiency.

\(^{91}\) This theme is echoed by neurologist Jean-Pierre Changeux, in Ricoeur and Changeux (1998).
Recent molecular genetic studies of neurotransmitter regulation are providing new insights into pathophysiology of violent behaviour. Functional anatomy of neurotransmitters involved in the regulation of violent behaviour is being studied with recently developed brain imaging methods (Volavka, 1999).

And the biological substrates of different types of behaviour are sought in the brain. Raine et al. (1999) found distinctions between different kinds of murderers (predatory and affective):

"results support the hypothesis that emotional, unplanned impulsive murderers are less able to regulate and control aggressive impulses generated from subcortical structures due to deficient prefrontal regulation."

The association of brain scanning and the molecular level of study is also made in terms of studies (especially with PET) which use tracers others than H215O. Functional anatomy, when linked to neurotransmitters can therefore be integrated to a genetic discourse, which addresses the formation in the brain's sensitivity to neurotransmitters. Furthermore, it links this type of brain mapping to yet another powerful discourse of biologisation of mental illness: the pharmacological approach arising in the eighties and nineties. ⁹²

Mapping as Way of Knowing

Brain mapping can be described as a reductionist strategy, where one level (cognitive process) is defined by a more basic one (brain metabolism and structure). While these scans are brain-based, and as I have argued, introduce new aspects of the mental into the biomedical systems that deal with the brain, the new maps are also introducing notions of the mind-in-the-brain to these practices. The resulting maps are not impoverished representations, but rather surprisingly productive ones: if the mind can be traced in the brain, then the factors that affect the mind can also be mapped. There is therefore both a shrinking of the mind and an expansion of the brain, as environment, development and even individual experience come to be placed on the map, as an articulation of the relations between structure and function. The making of maps is furthermore embedded in a particular armamentarium of brain imaging technologies, which served to create and, increasingly, to test these relations.

These new representations and their embedding in systems of care and surveillance can be understood as part of a larger dynamic that began in the sixties and seventies, and has grown with the more recent digitalisation of medical and communication technologies. These new maps, (like the genetic ones with which they link up so well), are instances of what Castel has described as a move away from

⁹² As explained in chapter 1, these studies performed with ligands have developed into quite a separate research endeavour from 'water studies', which form the topic of this thesis. They are therefore only mentioned here, but Rose (1998, 2000) addresses some of the applications of brain imaging to the study of neurotransmitters.
contextualisation, and towards an instrumentalised approach to the environment and the individual as a sum of diverse factors. Such approaches have as a further consequences to focus on “non-anthropological” aspects which can be decontextualised (Castel, 1981). The examples discussed in this chapter, however, make one wonder as to what, if anything, might not be ‘decontextualisable’. Maps that show the mind-in-the-brain become the space of human possibilities, with the modulations of environment, circumstance and heritability as mappable factors. The social, here redefined as a feature of the space of the brain, becomes a territory for the modern project— the deployment of ‘empirical analysis and planned change’ (Rabinow, 1989).

In terms of the research context at the confines of cognitive psychology and neuroscience, in which these maps have developed, these new representations involve the translation of the brain into a digital space, and the construction of activity (the life of the mind) into the image of blood flow distributed over the space of the brain. These maps link differences in performance of a pair of tasks, and represent this activity as meaningful. Processes of digitalisation and biologisation are therefore at play in producing these new maps which are the locus of new developments in the bio-medical management of mental phenomena.

Beyond research settings, these shifts are culturally meaningful. Think back to the research on bilingualism, the highly idiosyncratic embedding of a second language in late bilinguals, and the highly responsive audience encountered at the beginning of this chapter. To understand the ability to speak a second language as a feature of the brain involves shifts in the way individuals have traditionally related to their biographical trajectories. It is the significance of these shifts that fuelled the vehemence of discussions in the episode with which this chapter opened. Maps of the mind-in-the-brain are therefore the result of a number of shifts bridging the possibility of seeing the living brain (which is what the technologies arguably provide) and the even more far-reaching possibility of seeing one’s life in the brain, which involves the many other aspects of brain mapping described in this chapter.

---

These factors for Castel are to be scrutinised by specialists, who are able to look into places not available to layperson. See also Terry and Urry (1995) for a discussion of the privileged gaze of the expert.
Chapter 4 Images Are Not the (Only) Truth

This chapter considers a love-hate relationship between scientists and their object: the case of the iconoclastic imager. It considers this paradoxical stance as the result of the formation of an interdisciplinary approach that brings together a number of scientific traditions and their particular standards of what constitutes scientific evidence (its 'empires'). By examining the various ways in which images are deployed and rejected, I will trace some of the origins of these conflicting tendencies to the technological, methodological and institutional elements in the work of functional imagers. Beyond 'making sense' of this paradox, anthropologically speaking, this chapter will provide insight into the current demarcation of imaging with regards to the medical and scientific communities. Since that demarcation primarily revolves around the use of representations, it will also contribute to the discussion about the growing use of authoritative imaging in technoscientific culture. As any and all images become possible, there remains the need for guidelines for "choosing which permutations are acceptable—regardless of technological feasibility (Stafford, 1996)." It is precisely such a case of complex rule-making that I will examine here.

In order to make this argument I will be considering changing and contrasting definition of what I, as a student of the visual, would call 'images' in brain mapping. I will use the term 'representation' to describe this changing object which has different meanings in the neuroscientific sphere, in the popular domain and in my own discussion. This term will allow me to discuss the ways in which meanings are contested, negotiated or simply taken for granted. It will allow me to highlight the unacknowledged work performed with representations—the work involved in inscribing them in a pictorial or graphical tradition, of making them pictures or graphs. Finally, this neutral term may also be a useful boundary object with which to enter into a dialogue with the various groups who produce these representations.

Types of representations of scientific knowledge have traditionally been ordered hierarchically in modern Western Science, with images and some forms of visual knowing generally low on the scale (Stafford, 1991, 1996; Cartwright, 1992, 1995). This hierarchy relies on the ordering of ways of knowing the world, which provide better or worse access to truth about the way things are, appealing merely to the senses (perception) or to the mind (reason). This ordering of image/text/number is not absolute, however, and there are other ways of constituting visual representations according to linguistic or quantitative logics (for example as graphs) which enhance their status by associating them with a quantitative ethos. Digitalisation of scientific data, as analysed elsewhere in this thesis, is associated with the quantification of the visual, constructed as a form that supports a graphical representation of quantities. As I will show in this chapter, without the indication of scales and statistical significance of measurements, representations in functional imaging are at best 'pretty pictures'. Discourse has become
calculation in the digital age, the word subsumed to number, quantitation preceding explanation.

Such hierarchies have a history and cultural logic, which has been pursued by a number of disciplines—philosophy, art history, sociology and anthropology, etc. Two threads of this history will be most relevant here: studies which have shown an association of disciplinary identity to ways of knowing, and those which have addressed the place of visual knowledge in relation to other ways of knowing. I am not so much interested in the ‘epistemological essence of knowing’ but rather in the ways these representations are used to mark the work of brain mappers and carry their knowledge claims.

Some scholars in science studies have demonstrated that the notion of “epistemic cultures” can be used to characterise forms of research (Knorr-Cetina, 1999; Loewy, 1992). Other have shown the need for groups to maintain an identity in order to have their particular contributions recognised, and to claim scientific or professional authority—with practical consequences for obtaining resources. Such an identity can be built through demarcation work, by using rhetorical strategies (Derksen, 1997). Demarcations must yield more than simply the possibility of having an enclosed circle in which to develop scientific theories—it must also create a ‘demand’ for a particular kind of knowledge or expertise (Derksen, 1999). In the case at hand, the format of the knowledge claims of researchers will be shown to be reconfigured in particular contexts, to better create such a demand. The boundary objects used for this purpose can be problematic in and of themselves. Derksen has shown that common-sensical notions used by psychologists are considered to pose particular difficulties, because they belong at once to the rhetorical set of tools used to reach out to a lay audience and to the domain of investigation of psychologists. The use of representations will be also shown to be problematic in that these can also be understood by a lay public while forming the basis of scientific investigations. In both cases, the immediacy of understanding, the very effectiveness of the medium that conveys the expert’s knowledge to non-experts, challenges the expert’s status by virtue of seeming to make this knowledge directly accessible.

Some researchers have focused more specifically on the links between professional aspirations of groups using visual evidence. Galison’s study of two contrasting traditions in microphysics identifies a ‘logic’ and an ‘image’ tradition, and on the basis of the instrumentation developed by each, traces the contrasting epistemics with which knowledge claims are made and transmitted. The two traditions merge with the

---

94 Sargent (1998) signals that philosophers have recently begun to consider that scientific work might also include non-linguistic elements in the cognitive and communicative activities of researchers (See also Gooding. She also explores how brain mapping might be a fruitful terrain for investigating such questions
95 But see Lynch (1991).
96 Researchers using imaging very occasionally reflect on this topic, and occasionally mention Crease (1993) or some the work by Tufte (1983, 1990) to point to issues in representational strategies, but they do not integrate these insights to their practices.
97 Galison looks at the two competing traditions of instrument-making in modern physics: ‘images’ are mimetic, purport to preserve the form of things as they occur in the world, and are ‘homomorphic’, while
digitalisation of instrumentation, which allows both a quantitative and imagistic approach to be combined. Galison’s work highlights how these traditions endure, through three levels of continuity: pedagogical ('family trees' of students), technical (day-to-day skills), and epistemic or demonstrative (ways of arguing, of demonstrating). The last dynamic, claim-making, will be the focus here.

Another point from Galison which is relevant to this discussion is the privileging of the ‘image’ tradition’s results in popularisation (of discoveries of new particles, etc.). Images are rhetorically powerful (in a Latourian sense) to carry the existence of new phenomena into new realms (Galison, 1997). I have discussed elsewhere how this is also the case for brain imaging, through reliance on an understanding of the visual which is based on photographic realism. Here, with regards to both the scientific community and ‘the public’, I will argue that ‘images’ are not only powerful, but also dangerous, because of their role as boundary-objects which place them at different points in the hierarchy described above.

Pasveer has also analysed the creation of a ‘representational practice’, one involving x-rays, but also many other nodes in a network (Pasveer, 1992). Her description of complex dynamics needed to make something count as evidence highlights how representational strategies are best understood as part of networks, where meaning-making occurs in relation to other types of evidence, rather than in relation to ‘the world’ (Pasveer, 1992). The rise of new objects of knowledge as the result of mutual construction of technologies, professions and representations will also be shown here, especially in the second part of the chapter. Insofar as the notion of a hierarchy of evidence is invoked by functional imagers, however, this analysis will stress contrasts with existing practices and groups rather than the construction of new objects (but see chapters 2, 3, and 5).

From a cultural studies perspective, Cartwright has analysed the use of visual empiricism by neurologists in America in the first half of the 20th century. The professional anxiety of neurologists, and their recourse to a visual approach of surface classifications, can be linked to the growing threat posed to their professional domain by psychoanalysis, and its aural empiricism of deep phenomena. The production of a new gaze for beholding bodily surfaces through the use of cinematic technologies can be understood as an attempt to reinforce the traditional neurological approach of visual classifications. These classificatory tools did not succeed, however, and remained marginal (Cartwright, 1995). Here, the use of visual evidence will be discussed not as a defensive move but as an entrepreneurial one, where functional imaging tries to establish its domain of competence among existing disciplines. This brief review therefore points

‘logic’ uses electronic counters to make statistical arguments for the existence of a particle or effect and are ‘homologous’ representations (Galison, 1997).

This hybrid state of physics instrumentation (electronic counters used to produce visualizations) is very much the starting point of PET brain imaging technology (around 1975).

See Beaulieu (2000) for a discussion of the popularisation of imaging.
to the possibility of analysing professional distinctions (and the aspirations of emerging disciplines) in terms of ways they promote their knowledge claims.

Other researchers who have considered functional imaging have also noted the importance of representations in the functional imaging community:

"Yet, the cross-point is a picture. For the runners the picture is an end. For the users the picture is a starter. The more accessible the meaning of the picture is, the most powerful are the discourses and actions generated on its basis. Therefore, the unifying interest of both runners and users is to improve the quality and the veracity of the picture, since the existence and the welfare of this hybrid world depends on the promotion of the *high status of this picture* among the profession and the public at large."(Anguelov, 1994)

My analysis will demonstrate the contrasting definitions of what constitutes "quality and veracity" in the various disciplines in which functional imaging is used. This makes the demarcation work, on which the existence and welfare of this hybrid world depends, extremely complex.

**What Representations Can and Cannot Do**

Researchers involved in brain imaging have a complex understanding of the representations they use. They strive to make their brain scans, maps and atlases quantitative and therefore scientific, but also try to hold on to some imagistic qualities of these representations, namely, the evocation of spatiality and the layering of data. The understanding of representations in the functional imaging community is characterised by a strong division between two possible functions of images, negative and positive. The first of these functions is explicitly denied to the image, and thereby defines it negatively: images do not form the empirical basis of functional imaging. Within this negation of the image, two main types of tropes arise, each positioning functional imaging in relation to scientific ideals and demarcating functional imaging from less scientific endeavours. The first redefines the image as a representation of quantitation, and aims to establish the scientific foundations of the research pursued ("they're not pictures, they're statistical maps"). Related to this theme is the constitution of the research as independent from the imaging technologies used (not pretty pictures). A second group of tropes distinuates the work done by researchers from the clinical applications of (PET) imaging ("this is not a radiological science") and the nuclear medicine origin of PET. A second, communicative function, is discussed later.
Trope 1: “They’re not pictures, they’re statistical maps. So you’re showing hard evidence.”

The quotations below are taken from interviews with senior researchers. Associating things visual with functional imaging angers them:

“Dumit: Do you have a favourite image?
T-P: No!
Dumit: I was curious. Do you consider yourself a visual person?
T-P: (pauses) Probably yes, but I have to think about that.
Dumit: right.
T-P: Let me put it this way. If I look at an image or at numbers, I am more concerned with what it represents than how it represents it. I don’t know if that answers your question, but I am trying it (Dumit, 1995).”

AB: Now PI{T} is a visual technology. what do you think the promise of that is--
Researcher: PI{T} is a visual technology?
AB: Huh. an imaging technology--
Res: Why do you call it a visual technology? why do you want to associate vision with imaging?
AB: Hum [pause]. I’m afraid I wasn’t neutral enough. PI{T} results take a visual form. Do you think that is an important aspect?
Res: No, I don’t! Actually it’s sort of a radiologic misnomer.

Pacifying work on the part of the interviewer is needed to maintain dialogue between clashing conceptions of what is going on in functional imaging. The abundance of representations in neuroscientific contexts which overwhelms the neophyte,\(^\text{100}\) clashes with the conceptions of researchers that they are involved in making measurements in the brain, not obtaining images of it. An interesting exception I encountered to this attitude among researchers had to do with a once-off experience, often marking pioneering moments. In such cases, the researchers acknowledged the significance of seeing, when the visualisation enabled by the technology led to a kind of witnessing. For example,

[the visual] had an initial impact. it was extraordinarily exciting to see things that had never been seen before. I remember several occasions at the Hammersmith, where we saw things that no one had ever seen before. Like the substantia nigra

\(^{100}\) I recall jotting down in my notes that I was seeing more images at my first brain conference than at any film or art history lecture I had ever attended. This contrast between the empirical basis and the mode of expression can also be explained at least partly by the association of hierarchies of ways of knowing—art historians seek to heighten their insight into art through linguistic expression of their visual understanding, while brain imagers, having a stronger empirical basis, relatively speaking, can afford to make their expression visual. I am also a participant in this—the first version [and now final] of this chapter contains no illustrations. Gould notes in passing this distinction in rhetorical style of scientists and humanists (Gould, 1998).
working. So there is an impact, which I guess is the same as the impact of looking through a telescope and seeing something that no one has ever seen before, the impact of the moment when looking at a comet, which is extraordinarily exciting to see... (Senior Researcher, trained as psychologist).”

The sensory is associated with experience, the moment of discovery or first observation, and not with reasoning. Here is another example, particularly interesting for its use of an aesthetic vocabulary:

“Nothing can quite describe our excitement during our first scans in seeing how specific the brain's activity was and how beautifully it adapted to the requirements of the task (Posner and Raichle, 1995).”

A sense of wonder is associated with seeing when related to a particular event. Here, a representation again marks discovery at a point in time:

‘See that?’ gestures Dr. Michael E. Phelps, the Jennifer Jones Simon Chair in Biophysics, pointing to a framed cover of a 1982 edition of Science on his office wall. ‘That was the first time anyone has ever shown functional mapping of the brain in living people.’ (http://www.bruin.ucla.edu/feature/challenge/maptext.htm).”

But ordinary day-to-day practice of scientific investigation does not fall under such a category. Seeing is not the ordinary technique of investigation; one does not do this work because one is visually oriented.

Researchers insist on the fact that they are not involved in observation, but in measurement work. Speaking of representations in PET scanning, this researcher explains that “they're deceiving to some extent because if there’s no hard statistics underneath, then they're just pretty pictures. (Senior Researcher, trained as neuroscientist)”. The data of research is described as quantitative: the work is done using “a coloured representation of a set of statistical values” (Junior researcher, trained as physician). Explanations of representations focus on the measurement work involved in making scans:

“As far as I'm concerned, we are doing serious quantitative systems neuroscience. We are very conscious that we are doing 3 and 4 dimensional data analysis. The fact that the data is representable in an appealing visual form is extra... (Senior researcher, trained as physicist).”

The visual in the quotation above is described as almost accidental, an emergent property of the quantitative data. The data are measurements of phenomena, and they define complex phenomena in a way that visualisation could not achieve. Here, a researcher contrasts visualisation work, where a representation used by a surgeon is based on a
correspondence to the brain of the patient, and an activation study, where the referent is a set of complex measurements:

“But for, I don’t know. Cognitive activation paradigm, you want to measure what structure is being used. And there, because of the statistics involved, because of the noise involved, it’s a quantification problem. Some of the things they’re looking at now are so subtle that [they’re] trying to figure out whether it’s real or whether it’s not (Researcher, trained as computer scientist).”

An anatomical reality can be apprehended visually, but complex psychological phenomena must be measured and rendered quantitatively. The instrument’s use and the understanding of the representation are aligned, integrated in a quantitative mode. This insistence on the quantitative is one of the strategies that prevents the “proliferation of meaning”, prized by artists and not by scientists (Bastide, 1990), narrowing the possibility of interpretations that can be made of the results. Although the representation can be altered, made to look better, its referent is solidly quantitative:

"...particularly now with image editing and enhancing, you can manipulate images, and ultimately, one should be able to track everything back down to tables of numbers which are locations of activations in Talairach space, it’s the sort of concept that underneath a glossy exterior, there’s a strong skeleton, that refers back to [inaud] that is what gives some coherence and credibility...(Senior researcher, trained as physicist)."

Joe Dumit (1997) labels this reliance monosemy, a quality of the information provided by scans, but more generally it is also one of the main features built into the neuroscientific understanding and production of representations.

The rejection of the visual and the embracing of the quantitative referent involved is often done in the same breath, evoking progress:

“but I think that for a field to grow up--and everybody thinks the same, I don’t think I’m giving you views that are different from anybody else, in the best places, I don’t think I’m putting forward views that are the slightest bit heretical--it becomes important that it become quantitative, science doesn’t just deal with pictures it deals with counting things, graphing things, plotting things. (Senior Researcher, trained as psychologist)"

These arguments for the quantitative nature of data and against the visual component can be seen as a positioning of functional imaging as a scientific endeavour. The representations used are renderings of quantitative measurements, and stand for complex phenomena. The researchers therefore align their empirical basis, the scans and maps they use, with a quantitative and experimental approach, rather than a visual and observational one. Brain mappers perform experiments where brain functions are variables, where responses are tested statistically, and group data carefully analysed. In their
understanding, a ‘visual’ label reduces this work to ‘observation’. Such observations might be useful for the neurosurgeon, who must plan an intervention—but not for the scientist.

Even within research activities using PET, there is a hierarchy from more to less quantitative, depending on the way measurements are made: “There are conflicts between those who use it qualitatively and superficially and those who use it analytically, by their nature.” (Phelps in Dumit. 1995) This researcher then goes on to contrast various types of research, and the likely reaction of neurochemists (from the highly quantitative end) to clinical research:

“‘I don’t like that, you don’t know what you are talking about. What are the units of your data, depression on this axis versus colour on this axis?’ So there are a lot of factions within PET, because it does go from basic chemists and biologists to clinical investigators, and their criteria of an experiment is quite different (quoted in Dumit. 1995).”

These differences of criteria of an experiment can be traced in my analysis, not only within different groups using PET but also with the neighbouring groups of researchers. A frequently recurring expression (already encountered above) in discussions of representation is the phrase “pretty pictures”.

[speaking of the visual, the interviewee has just explained how it is significant for communicating with the public]

AB: But it’s also valued among scientists.

Int.: Within the field we know what we are doing. I’m talking about at one removed. If you’re not in the brain imaging field, it’s very easy to dismiss brain imaging as pseudo-science. Those of us in the field know what those pictures, which are so pretty, underlie, what they represent. I’m not saying that is not something that is usable scientifically …. (Senior researcher, trained as physicist).

The description of functional imaging work as making “pretty pictures” invokes again an accusation of lack of scientific purpose, through associations with a non-scientific, visual and ‘photographic’ approach. This pejorative description is often heard coming from psychologists who critique the way ‘function’ is studied. Making pretty pictures of the brain is at best observational, and not the scientific study of function through the complex experimental designs prized by psychologists. [v]

[v] This complex experimental design especially focuses on manipulating tasks so that ‘functions’/processing stages/operations can be distinguished. Cognitive psychologists focus on very specific components of tasks, for example distinguishing visually presented animals from visually presented tools. Functional imaging has investigated functions at a less specific level, with early experiments distinguishing ‘cognitive’ from ‘visual’ activations for example. More recent work has produced more sophisticated activation paradigms, but the degree of specificity in tasks performed in still not as great as in cognitive psychology. Cognitive psychologists also focus on measures of time and error/accuracy of responses. This contrasts of measurements in time and space will be further discussed in the second part of the chapter.
The phrase, “pretty picture”, has links to the previous trope, since it points to the sensitive issue of (lack of) scientific sophistication. It also relates to the next trope, since it defines brain mapping work as dependent on the technologies used, invoking the passive photographer whose apparatus does the work. The prominence of technology in functional imaging is difficult to overcome: a PET scanner and cyclotron cost up to 7-10 million $US, and around 1500$US per scan. This is especially true given the low tech context in which much of this work is done. Functional imaging is ‘little big science’, whereas psychology and neurology are not highly technologically-dependent fields of research. This over-identification with the technologies they use is countered in general ways by functional imagers by insisting that functional imaging has moved into mainstream neuroscience, and sometimes seeming to avoid ‘imaging’ in describing their work. More specific strategies will be discussed below.

In terms of the status of representations, therefore, functional imagers argue for a quantitative definition of their representations. Representations, when understood as part of an imagistic register, are only accepted as part of moments of discovery. Otherwise, a discussion in visual terms of the representations used by imagers is considered a lack of understanding of the approach and phenomena these researchers are investigating. Sometimes, such descriptions are precisely aimed at questioning the status of the research (just ‘pretty pictures’). But, for brain mappers, the proper understanding of functional imaging is to see it as an experimental strategy that measures and explores the brain quantitatively, not one that visualises it. Interestingly, researchers also connect an explanation for the use of “the visual” or visualisation to the complexity of their quantitative data—their data is the result of complex quantitative relationship that can best be rendered visually.

If representations are quantitative, the proper way of understanding them must also involve a quantitative rationality. This is the basis of the second trope.

Trope 2 “I have no truck with people who look at images and interpret them.”

This trope also negates the visual, but it is directed at a different kind of demarcation of these scientists’ work, setting researchers apart from the clinic. The clinicians are image-oriented, to the researcher’s chagrin. Measurements in quantitative form should be enough to understand the scans, but they are not:

102 There are other parallels to be drawn with big science. In the eighties, there were discussions about setting up a large brain centre, CERN style, in Europe.
103 Arguments about the need to distance the research endeavour from the technological means also arose in discussions around the setting up of the Organization for Human Brain Mapping. The setting up of a professional organization based on the common use of technologies was resisted as unnecessary or even a dead end. A loose association was chosen over a strong professional organization.
"In our clinical work, we provide a list of all brain areas, the metabolic rate for that patient in that area, and the normal range for that area based on our files. And whether that person is plus or minus two standard deviations of the normal range for each area. We also provide the colour images because the physicians want it, but we would be happy on our clinical reports just supplying the numerical information (quoted in Dumit, 1995)."

Clinicians therefore desire a beautiful image of the brain, a desire Dumit has analysed as a culturally-based longing for insight into what subtends our personhood. But the clinician’s desire is the researcher’s aberration. It reduces the work to scan-making, a technicians’ occupation. A quotation above indicates that to link PET and vision is a “radiologic misnomer”. This opposition to radiology recurred several times in interviews:

“...I think that in the field that I’m involved in, which is functional mapping, we have maintained the tradition of quantitation, even if it’s relative quantitative or statistical level quantitative, and SPM has been critical to that. So there’s no question we would simply inspect images in a radiological sense to make diagnosis or conclusions. That’s just not in the ethos at all of what we do and it’s never been in my ethos (Senior researcher, trained as physician)."

“And they [spm’s] do not signify and do not require the sort of interpretation that a standard radiograph might (Senior researcher, trained as physician)”

A number of threads can be followed to explain these moves to distantiation from the clinic. First, it is a distinction that relates to the history of the development of these scanners. PET scanners were developed in nuclear medical settings (see chapter 2) and while a number of potential uses were suggested, the most enthusiastically pursued was that aimed at tumour detection. But even within the early research on cerebral blood flow, there were those working in the tradition of auto-radiography and those oriented to nuclear medicine. At this point, it seems that the clinical and research distinctions were already articulated along the lines of image versus number. In this passage, one of the

---

104 See Dumit (1994) in which he analyses the cultural longing for and implications of imaging the brain.  
105 In relation to PET, some of the early goals in nuclear medicine were to develop a tool that would compete with x-ray CT, for example by allowing imaging of structure of organs that could not be detected by x-ray (Wagner, 1992). Raichle recounts the efforts as trying to regain ground lost to CT: “Nuclear medicine brain scans, which had been a staple of the practice of nuclear medicine, were quickly replaced by x-ray CT (Raichle, 1996).” There was also a tension between the clinically oriented imagers and those who wanted to do autoradiography in humans with it. Raichle argues the right course was to hold off from clinical applications, because it did not provide anatomical data that was already understood clinically, but rather measurements that were not... The link between the measurement of brain blood flow and brain activity was not a significant part of the PET agenda until about 1984, and it became a measurement of ‘cognitive’ processes a few years later. Mature PET (in a technological sense) had already been developed for ten years at that point.
pioneers of the methods on which PET is based. Louis Sokoloff. was said to be uninterested in detection by imaging. He reaffirmed the alignment of science and measurement, citing an aphorism by Lord Kelvin that hangs on his office wall, “When you cannot express it in numbers, your knowledge is of a meagre and unsatisfactory kind (Kennedy, 1991).” The move towards complex quantitative analysis processes is also considered part of the development of functional imaging research.

The marked contrast between research and clinical goals of diagnosis/research is also expressed in debates about the very way in which these representations are to be understood. In the eighties, a debate around the interpretation of PET scans was fought out, between the quantitative and visual approach to PET scans, at a workshop on PET analysis and in journals. One side claimed that clinical PET can produce representations that can be understood visually: researcher insisted on a quantitative measurement and a quantitative evaluation. In this debate, PET scans were seen as highly processed data— involving normalisations, statistical tests and the use of complex models. Clinicians argued that certain elements of this process might be bypassed without compromising the validity of scans and with the benefit of increasing the clinical usefulness of PET. One commentator described the production of PET scans in its (original) research context as a chain of events, which, while theoretically improving the data, might not have clinical, biological relevance (Di Chiro, G. and RA Brooks, 1988).

The researcher’s analytic approach was not welcomed in the clinic as impractical, possibly unnecessary, and often unfeasible. One reviewer summarised the clinical side of the debate as follows:

“too much emphasis has been placed on sophisticated statistical analyses and not enough on common sense. If no difference is seen visually or graphically, then it either does not exist or it is too small, compared with methodologic error, to have great significance (Aine, 1995).”

Furthermore, even when no objections were raised against quantification as being overly complex, the visual appearance was argued to be an even better basis for judgement than quantitative indications (rates described in tables and lists):

“The visual appearance of the tumour is a far better guide to tumour grade than the absolute metabolic rate (Di Chiro and Brooks, 1988).”

---

106 Husband of nurse and aircraft pilot Betty Kaiser, Louis Sokoloff worked with Ketty and Schmidt at University of Pennsylvania, and later at the NIMH. He is said to have inspired the ‘fathers of PET.

107 A stream of STS research analyses the professionalisation of vision, (seeing as a learned activity and not as a self-evident, biologically-determined sensory activity), and the codification of the understanding of visual evidence. Vision is shown to be the result of various social, interactive processes and not a given perceptual attribute. This last body of scholarship includes both analyses of the historical formation of vision (Crary, 1991; Cartwright, 1995; Pasveer, 1992; Kember, 1991) and of professionalisation (See footnote 13).
Another way of understanding the importance of the distinctions researchers make between visual evaluation and a quantitative approach is to look at a proposal for crossing this boundary. Writing in the *Journal of Neuropsychiatry and Clinical Neuroscience*, clinical researcher Andreassen proposes going from a 'clinical' to 'research-oriented' use of imaging. While "many of these techniques have been developed and marketed as clinical tools to permit physicians to look and render a judgement as to whether a structure or functions is normal or abnormal," the clinical tools can be adapted to serve research purposes (Andreassen et al. 1992). The transformation consists in retrieving the quantitative:

"Essentially, the challenge of image analysis is to convert information originally meant for visual gestalt processing into a quantitative and mathematical tool that provides precise estimates of structure size, shape, volume, or physiological activity (Andreassen et al. 1992)."

Andreassen's lab offers a number of tools for this purpose.\(^{109}\) Note that not only does the understanding change (from visual gestalt) but also that 'precision' is to be gained and discrete elements to be measured (size, volume, etc.) rather than an understanding of the whole—a gestalt image, presumably of a normal or abnormal brain. While the focus here is on the main quantitative/visual distinctions, a number of features of imaging could also be shown to contrast between lab and clinic: the use of colour for example\(^ {110}\). To go from a clinical image to research data, one must shift from looking to measuring, from visual understanding to quantifying.

---

\(^{108}\) See note 107. The clinical gaze is not itself simple, unproblematic. There are 'rules' for visual understanding, which are also embedded in technologies and histories.

\(^{109}\) Andreassen notes that observer intervention is sometimes necessary in using some of these tools, but she also redelines seeing in mechanistic terms. The observer is also described as 'technically' incorporated into the machine in another article on an analysis tool developed by the Evans group: "The methods described here seek to take advantage of the pattern-recognition qualities of the human eye with noisy, low-contrast anatomical images while adhering to a pre-defined framework for anatomical mapping. (Evans et al. 1988)." As these notions are set in a context where technologies of vision grow in importance, these relations are partly reconfigured, so that perception is best replaced by automated tools which never fire, which feed reason only the most rational of percepts, images of numbers.

\(^{110}\) Besides colour, there are many other 'conventions' for these representations—such as 'view', slicing, or the use of shading, etc. The development of conventions for the use of colour in medical imaging would deserve a book length study. (See Kevles (1997) for a sketch of some of the issues, especially pages 207-8). Robert Savoy, of Massachusetts General Hospital, explained in a lecture at the human brain mapping conference 1996 that the use of colour for medical imaging is not allowed in the US, because it turns quantitative differences into "categorical variables." Quality and quantity clash. The 'rainbow question' has often been posed to me, most succinctly by a historian of psychology and things visual ("how did the brain get its colours?). Yet, it is not an issue that seems to be of interest to the scientists—the colours are 'simply' from 'the packages', etc. I would suggest, however, that the use of grey for structure is part of the x-ray esthetic, (which may have developed based on the kinds of chemicals that were used to coat plates) and the colours as 'the juice', the activations. I have also observed that other spectrums, like 'hot metal' are also used chosen for activations over grey schemes, though they retain the element of gradated colours.
Those ‘who look at images an interpret them’ are therefore clinicians using PET\textsuperscript{111}. They are those who have different (or less) technological support, a different expertise and goals that clearly differ, though they use some of the same technology. The arguments about the visual/quantitative understanding of these representations express the depth of these differences. The debate about quantitation versus visual inspection seems to have subsided in the nineties, as research-oriented journals developed, on the one hand, and separate meetings were held.

The lab/clinic relations within the institutions where I did fieldwork were mirrored in the ways these distinctions were made and the ease with which lab/clinic boundaries were crossed (see Annex 1). In the institution where there was little interaction with clinical work, the distinction was firm (“I have no truck…”) while at the second lab, the opinions were expressed in more relative terms (‘different tools for different purposes’). Where relations with the hospital were problematic, the analysis software was strongly directed to a quantitation approach; the documentation accompanying the software explicitly stated that it was not meant to be a bio-medical imaging package. The programming language used to write this software is also much better suited at handling matrices than images, thereby incorporating the distinctive research orientation into the tools of the research centre. At the second centre, where researchers were much more involved in clinical work, the analysis software was suitable for visualisation of individual patient’s scans, and biomedical visualisation work was considered useful. A work station capable of displaying this data could also be wheeled into the O.R. to allow the consultation of mapping data during surgery.\textsuperscript{112}

A further reason for this boundary work may be found in the precarious position PET has occupied as a clinical tool. As a very expensive technology, PET’s clinical presence has been particularly controversial in the Western economic context of the eighties (Kevles, 1997). But the costs have not been the only challenge to PET’s clinical acceptance. Technically, the need for an on-site cyclotron makes the use of PET a big enterprise even for academic/research oriented hospitals (Frick et al, 1992). The regulation of tracer production\textsuperscript{113} has also been perceived as threatening the wider distribution of PET scanners (Coleman, 1993). At regular intervals for the past 3 decades, PET has been said to be on the cusp of becoming clinical or of losing what little foothold it had acquired\textsuperscript{114} and has seen its clinical efficacy problematised or downright challenged.

\textsuperscript{111} With the following exception: Raichle speaks of looking at ‘raw data’, which can be useful to an experienced user—rather than always looking at thresholded images (significance-tested, normalised data.) In this role, scans are ‘exploratory pictures’ (Galison, 1997).

\textsuperscript{112} The development of neuroscientific tools that can ‘use’ images, (scans as visual representation), such as the probabilistic atlas, is a deliberate accommodation of the clinical form of scans. This is done in the hope of enabling more widespread use of atlases.

\textsuperscript{113} Especially in the US, the regulation of the radioactive tracers requiring them to be receive FDA approval as though they were ‘drugs’ has been bemoaned as holding back the spread of the technology (Coleman, 1993).

\textsuperscript{114} For description of PET’s trials, see Lumsdon (1992) Coleman (1993), Gershon (1995), and for PET’s promise, see Sawle (1995), Feindel and Yamamoto (1978).
(Powers et al. 1991; Volkow and Tancredi, 1986). Maintaining associations with clinical PET, which is challenged in terms of safety, clinical usefulness and economic liability, is therefore not appealing to research groups.

Claims to scientific status, and degrees of greater scientific legitimacy can therefore be understood by the rejection of definitions of representations that focus too closely on 'the visual', which is not scientific because not quantitative, which belongs in the clinic because of the understanding involved (judgement), and which too closely ties the work to imaging technologies and observation. These discussions of the role that representations do not play are therefore indicative of the ideals which functional imaging is pursuing. Furthermore, they also show how these ideals are embedded in the kind of empirical basis being considered.

Rhetorical Representations: When is a Picture Worth a Thousand Words?

A second, positive role is readily granted to representations, however, insofar as they function as tools for communication and not as an empirical basis, or style of evaluation. Representations are thus praised for their directness, and synthetic power, which imagers see as legitimately deployable in communications with colleagues or the public. Representations are especially suited for communicating results:

"The most profound use of computers in mapping is in the field of visualisation. Computerised visualisation of data that has been converted into a cartographic image of a spatial domain best communicates the meaning of quantitative information. Some people can see in their mind's eye the beauty and structure in mathematical or statistical relationships, but most require a visual representation to best appreciate these dependencies... (Toga and Mazzotta, 1996)."

These arguments not only limit the meaning that such representations can have (and prevent the undesirable effects described above) but they also reinforce the first trope, regarding the complexity of the data. Not only is the empirical basis of functional imaging quantitative, but the very complexity of the data calls for the visual presentation of results (visualisation).

"Wagner: [these studies in four dimensions] can only be abstracted and displayed in a meaningful way in the form of images. Otherwise there are too many numbers. Your brain can't really handle more than a couple of variables at one time if they are quantitative, so you have to have abstractions. And images are a very, very nice way of abstracting quantification (Dumit, 1995)."

Note the choice of an analytic, rational vocabulary—these are abstractions not pictures. Besides limiting its function to communication, researchers occasionally also provide an explanation for the efficacy of visualisation—an explanation grounded in the cognitive systems of the brain they study. The visual system is the sensory modality with the
broades tt  bandwidth , so the argument goes, therefore best suited to conveying complex data to the brain. By ‘totalling the observer’\textsuperscript{115}, the scientific process is extended by incorporating the physicality of the human body into the apparatus of scientific reason. The use of vision in relation to representations is rational, its efficiency explainable.

But the danger of improper understanding still lurks; credentials are necessary to be properly visual and scientific:

“But then there are people who believe it’s silly to show an SPM because you need to be an expert to understand an SPM, like showing an x-ray to a radiographer versus to a midwife who has no experience of chest x-rays. You need to get expert, and it can be dangerous to give too much information which may be interpreted in an intuitive manner rather than knowing exactly what is going on... But that is not my problem, my problem is to present data with great integrity and greatest validity...(Senior researcher, trained as a psychiatrist)”

“Let’s take an SPM. To the uninitiated, they will see a picture as an activity in the brain and at some level they will see that as the activity and they will forget that it has to be taken into account that that is not the activity, that is a coloured representation of a set of statistical values. And those values have been smoothed spatially, and in time, in the case of fMRI. They’ve been warped. They’ve been realigned. They’ve been through all kinds of crunch, and in setting out to simplify, the picture can to some extent deceive. (Junior Researcher, trained as physician).”

To see a picture as transparent is not an appropriate way of seeing, so that even when quantified, the measurements must be understood in terms of their production, not simply in terms of the phenomena they represent. This responsibility to see properly echoes what I evoked as one of the enduring aspects of modern concepts of scientific ideals earlier: reason’s duty to monitor the senses. This notion surfaces in moral terms, where, in the face of the development of more and more imaging technologies, scientists must bear the responsibility of proper scientific knowing and not be deceived by the transparency of images (Crease, 1993). An image, the argument goes, can fool you into thinking you understand an object in a way a graph or measurement wouldn’t. This aligns rationality, proper understanding and moral responsibility as one mode of dealing with images, and intuitive understanding, uncertain knowledge and seduction as another.\textsuperscript{116}

\textsuperscript{115} The phrase is from John Tagg, (1989). See also Jonathan Crary (1992) and Sarah Kember (1998) for analyses of displacements of the observer in relation to technologies of photography and digital imaging.

\textsuperscript{116} For example: “You have to be careful not to be seduced by the images. You have to understand, from the scientific point of view, that the paper you write, you are not writing for Psychology Today. You are not writing for Newsweek, you are writing for the journals. You have to have statistics, and I have often said that, as fancy and compelling as the PET scans is, you still need a good solid research design, with an adequate number of subjects and the right statistics (quoted in Dumit 1995).”
Yet, in other settings, it is precisely the seduction of the viewer through an intuitive understanding of representations which enables functional imagers to communicate effectively. Researchers acknowledge the efficiency of representations in drawing the attention of the public to their work, though the lay public will understand them differently. The impact on the public can be great:

“No, the thing that’s handy about it though, is that because you can make pretty pictures it’s easy to get across some of the information to a lay public. Which in times when science is being sliced and diced, it’s always nice to be able to have science published in a lay journal—even if they screw it up a bit. It’s, I mean, an energy physicist would have a very hard time trying to justify why they need more money, why they need millions of dollars more to go identify another subatomic particle, and we can show pictures of the brain lighting up or not lighting up, and some activation paradigms, and it’s easy for someone to understand. They can see the importance, as opposed for instance to finding some subatomic particles.

(Junior researcher, trained as computer scientist)

Arguably, physicists also find means to communicate with the lay public about their field—and this may even be through their own “pretty pictures” (c.f. Galison). But such effects, which scientists attribute to the images, are not trivial. ^7 What I wish to highlight here are the demarcations that researchers themselves make in relation to representations. Though the effect may be desirable, representations outside the proper scientific and professional settings will not have a rational impact:

“You can put out all the words in the world, but a picture is very powerful in communicating the information. So it is a medium that on the one hand allows you to communicate more easily with the public but on the other you can start imagining things from this image that aren’t real (Phelps in Dumit, 1995).”

“I think between scientists, they are less easily impressed by the picture…. I mean, it’s a quick reference point, but then you want to know a lot more about it whereas Joe Public would look at it and goes: ooooh, this is what the brain does (Junior researcher, trained as physician).”

^7 It has been suggested that PET played a role in convincing a ‘chairman’ to support research:

“You are interested in anecdotes. Some time ago there was a meeting here, a relatively small meeting. Including Mr McDonnell, James McDonnell, who was a founder and a chairman of the board of McDonnell Aircraft. He was very much interested in the human mind. His hero was Penfield. He came to this university trying to convince people to get interested in the human mind, and, among other things, to get interested in parapsychology. Not many people in this institution are interested in parapsychology. So finally I think Mr McDonnell was convinced by a group of people, I was one of them, that perhaps PET is close to what he is interested in. And he helped out financially, and is still helping out through his McDonnell Foundation for the Neurosciences, some of the PET activities (Ter-Pogossian in Dumit, 1995).”
The image speaks for itself, but not in quite the same way to everyone. One of the consequences of this dual register around representations is that it allows neuroscientists to have it both ways: to make claims with scientific integrity while providing visually exciting materials for the public to understand 'intuitively'—and because of this understanding, gather further support for research. Lynch has observed a similar duality in the work of astronomers, also working a digital context, who produce both popular 'pretty pictures' and scientifically useful representations. The pretty pictures are used for rhetorical purposes, invoking an optical truth\(^\text{118}\) (Lynch, 1991). Lynch analyses this as a purposeful acting as a "community of the wise, sharing a secret understanding of non-apparent qualities while putting on a front for the sake of prevailing standards of taste and decorum (Lynch, 1991)." This is only part of the dynamic of the use of representations, however, and there are other (pro-active) aspects to the scientists use of representations for popularisation. Scientists are also conversant in the register of photographic realism and produce, when necessary, accounts based on such an understanding of these representations.\(^\text{119}\)

But the possibility of working both crowds has certain limits—the intuitive is not scientific and therefore dangerous. Other scientists also monitor the boundary between lay and scientific discourses, and functional imagers are aware of the possibility of a backlash:

Uncritically, everybody gets excited about imaging. It's a double-edged sword, because it's nice to get into the media but also sometimes tends to be denigrated by other scientists in other scientific domains as glitz and showboating rather than serious science. As far as I'm concerned we are doing serious quantitative systems neuroscience. We are very conscious that we are doing 3 and 4 dimensional data analysis. The fact that the data is actually representable in an appealing visual form is extra. (Senior Researcher, trained as physicist)

The restraint of scientists is therefore not only a question of being silent about the difficulties and contingencies of digital imaging, but researchers must also observe a certain restraint in presenting their work in non-scientific terms. This is not platonic rhetoric of techno-sceptics to denounce visual corruption, to use Staffords' phrase,\(^\text{120}\) but rather gate-keeping between the rationality of the scientific world and the intuitive reasoning of the public. When representations which scientists believe invoke intuitive, non-scientific modes of understanding are used, the threat is all the more powerful. This may add a further layer to Lynch's programme of understanding opticism in terms of "a set of instructions for performing actions in accord with the various optical knowledge-production machines; a disciplinary compliance on the part of the subjects in those

\(^{118}\) Part of the optical register is 'photographic realism'. The photographic effect, however, is arguably not intuitive, however, but rather depends on the viewer's familiarity with the conventions of photography. This is an understanding which to the Western observer has been exposed for 150 years (Mitchell, 1994).

\(^{119}\) They know how to use a pictorial vocabulary, and can talk about seeing the brain light up, looking at the brain in action, taking snapshots etc.

\(^{120}\) See Stafford (1996).
systems (Lynch, 1991)." This dynamic of backlash reinforces the scenarios of compliance with rationality (which is not visual) and the maintenance of the boundary between the scientific and the popular. The epistemes of functional imagers cannot include the purely imagistic, without renouncing claims to be pursuing quantitative, scientific experiments.

Researchers recast the discussion of representations from visual to quantitative terms to insist on the scientific character of their research, and to distinguish their work from other uses of representations, for clinical or popularisation purposes. This analysis shows that a number of factors affects the discussions of representations in a given scientific practice: measurements, location of research, technologies used, clinical versus research goals, scientific and lay understandings. While interesting in itself for what it tells about a particular scientific practice, and the yield that an analysis of negative statements can provide, I would like to press the issue of the use of representations one step further. These researchers are not entirely iconoclastic in that they do accept that images play a role, but they do fear too great a reliance on the icon—a seduction of the senses and the neglect of the greater truth that lies beyond representations. They are also wary of the accusation of being occupied with the making of pretty pictures, that come from other scientists. Yet, these representations endure. The argument that they are valuable as tools for rhetorical purposes does not entirely explain their continued presence. They are used in contexts that might not be primarily defined as communicative, for example, in data collection or data analysis. I therefore want to analyse in the second part of this chapter what further role these representations might play. I will argue that while an epistemic role is denied to representations, their use does make the contributions to the study of the brain specific to functional imaging. These claims to particular insight are based in the spatiality of the data. But this spatiality is achieved by using some of the conventions of anatomy, a domain where the pictorial and observational organisation of the work prevail—the very features from which functional imagers try to distantiate themselves.

What You Can Do With Images, That Others Can’t

Below is an excerpt from an explanation of the goals of functional imaging, where a strict definition of the epistemological basis of imaging is used by this researcher. This explanation was offered in reaction to questions about the importance of the visual, of imaging in using PET. This researcher was setting me straight about my misplaced interests, revealing in the process the link between world and measurement used by functional imagers:

What we’re doing is acquiring data. Every natural object, a tree, a human, a plane is in four dimensions, it has spatial extent, and it has behaviour over time. We’re trying to measure in those four dimensions. So instead of probing the brain by making one little measurement, say like people used to do with CO2 coming out of veins, that’s just a one-dimensional measurement over time. There was no 3-D component to that, so now we’re able to measure the brain more appropriately as a
3 dimensional object over time. So you could do that for the brain, you could do that for your foot, you could do that for anything. So the fact that we’re scanning in 4-D, is that particularly appropriate or inappropriate for the brain? It’s just the same as any other physical object... (Senior Researcher, trained as physician)

The brain is an object in four dimensions; the goal is to assess these dimensions. But, in this realist mode, the fact that the measurements are displayed over space is not relevant for the object, in the sense that it is not epistemically constitutive of it. (Note however, that the previous technique could only ‘probe’, make ‘one little measurement’.) In this description, a distinction between the object ‘out there’, and a given mode of measurement is maintained, so that the representation of the data is secondary. This is also a way of maintaining a distance between the scientific work and its ‘presentation’. A focus on the representation is missing the point:

Now, is that ever the point of any of these studies, is what the pictures look like? Not really. It isn’t. It gives you a good impression of the data quality, many people want to show a data slide, so people can get an assessment visually of the signal to noise. It’s hard to trust as data a publication in which you haven’t seen any of the raw data. ‘Cause it just might be noise. So if they show you their raw data in some form, you make an assessment as to whether you should pay attention to this study, or not. But beyond that what they’re talking about is what the mental operation was that they used, what the paradigm was, what trick they used to isolate this out, they may show you a picture to prove that a function that you thought was unitary is really two. And it’s two because it has different cognitive characteristics, different reaction times, or, and it’s two spatially, and I’ll show you a picture of it and it’s here and here. So the point is for you to look at that and to admire that it’s laid out over space? No the point is so you can see that there’s not a lot of overlap, that it’s two discrete areas and so two processing areas (Senior Researcher, trained as physician).

But without attributing the (entire) significance of the representation to ‘what the pictures look like’, I will argue that an important role is played by these ‘pictures’. It is important in many respects that these measurements are ‘laid out in space’. because this forms the basis of many of the particularities of functional mapping over other modes of measurement of the brain. ‘Where’ and ‘what’ are the questions answered by functional imaging, and they are questions that are answered through the use of representations. The representational practices of imagers are therefore embedded in the technologies used, in the experimental methods and in the knowledge claims they make, so that the ways of knowing of imagers are not separable from these representations.

I now wish to move my analysis from the more explicit discussions of representations in the first part, to look at the claims that functional imagers make in terms of the knowledge they produce about the brain. I will show how the arguments made about functional imaging’s particular contributions to the study of the brain cannot
be distinguished from the representational strategies described above. One senior researcher, trying to deflate my misplaced interest in representation, explained the constitution of representations in functional imaging as simply following the logic of putting the information about activity where the area lies in space (Senior Researcher, trained as physician). Nothing magic about it, said another researcher. But each of the elements of this strategy has a complex history. Each of these elements also participates in the claims of functional imaging in relation to other disciplines. The detection of activity, its attribution to an area of the brain, and the construction of a 'space' for relating these two elements are all based on representational strategies of functional imagers which differ from those used by other groups.

The research pursued with functional imaging technologies and methods is construed by its practitioners as the cross-roads between cognitive psychology and neuroscience:

"...it has come to the point, as it often happens in science, that a discipline arises between two existing disciplines. I don't think that will go away. The discipline is not PET and fMRI. It's all the methods for imaging, evoked potential, MEG, united around the fact that we can do things with the human brain that we never could do. ... It's not cognitive psychology, it's not neuroscience, it's somewhere in the middle..." (Senior researcher, trained as psychologist)."

The rest of this chapter will analyse how representations play a role in the way researchers construct a middle-ground between researchers of the mind and researchers of the brain.

\footnote{In order to check whether my own interest in the visual had not provoked many of these comments, I looked to other studies of PET to see whether these kinds of explanations were also offered—and that seems to be the case. Fragments from Dumit are quoted in the chapter, and the following quotation from an interview by sociologist Anguelov, exploring rather different questions (though related, because about 'world formation') contains the elements also evoked in the interviews I did. He explains:

Although PET is largely identified as 'imaging' technique, the fact of the matter is that the first step in PET is to collect quantitative data: every single positron emission is measured in a tri-dimensional space (and recently time has been added as a fourth dimension by the front PET researchers). It is at the next step that the bulk of measurements is digitally transformed into an image by the computer. But nothing can constrain researchers from using the data as measurements, i.e. in a statistical way. This trend is now gaining ground, and PET researchers from the MNI are at its leading edge. As a matter of fact, one of the leading PET runners was critical to the whole PET field that it still sticks to the image instead of providing more rigorous results from quantitative data only (Anguelov, 1994).}
Tropes For the first time in the history of neuroscience, it is now possible to ‘observe’ cognitive activity in the intact human brain.\(^\text{122}\)

Functional imagers stress the power of brain imaging technologies to encompass the entire brain of normal subjects. The space enclosed by the skull\(^\text{123}\) has been penetrated:

“These technologies have breached the biological limitations imposed by the inaccessibility of the functioning brain to direct observation and investigations, since they allow direct assessment of brain function in the normal living human being (Volkow and Tancredi, 1992).”

The elements of directness, in vivo study and normality which the technologies allow are considered truly unique to functional imaging. Furthermore, brain function has become more directly accessible. This is a common formulation of the powers of imaging. Being able to view the normal human brain, for example, has meant studying different kinds of subject:

“While CT was a means of viewing the internal anatomy of the human body, PET extended that view to organ function. Brain-behaviour relationships in human, long the provence (sic) of neuropsychologists and cognitive psychologists studying patients with brain lesions, could now be pursued with rather remarkable accuracy in normal subjects as well (Raichle, 1996b).”

Rather than relying on accidents of nature (strokes, tumours) that would affect function and thereby give some (indirect) information about the localisation of functions, researchers could study activations in normally functioning brains—function, rather than disrupted function. It also meant a different approach than intra-operative stimulations, which were done on patients with brain pathologies justifying such interventions. Furthermore, because the imaging technologies can retrieve the signal of the brain ‘non-invasively’, the space is undisturbed, considered normal. Again, this contrasts with the intra-operative stimulations, which are done on patients whose brains are affected by tumours or other abnormalities. This is also a shift from another ‘direct’ mode of study, which consisted in studying patients with lesion in life and correlating their dysfunctions with post-mortem studies of brain anatomy.\(^\text{124}\)

\(^\text{122}\) From Cabeza and Nyberg (1997).

\(^\text{123}\) The goal of penetrating the head with x-rays and the resistance of the skull was noted early on in the history of x-rays, as early as the turn of the century (Kevles, 1997). Attempts were also made with ultrasound (Yoxen, 1987).

\(^\text{124}\) A similar technique-based coupling of body and technology to produce a graphical mark was applied by Marey in physiological studies, also implying an important shift in methodology: the object studied and the production of the trace become interdependent (Cartwright, 1995).
Being able to see inside the brain space in vivo relies on features ‘built into’ the technologies used in brain mapping. Both ‘origin stories’ and technical descriptions of PET insist on the importance of the creation of the means for reconstructing images from the measurements made by the detectors. For example:

x-ray ct “immediately stimulated scientists and engineers to consider alternative ways of creating images of the body’s interior using similar mathematical and computer strategies for image reconstruction. This quickly led to the introduction of positron emission tomography (PET) which was in effect, a means of doing tissue autoradiography in vivo in humans (Raichle, 1996a).”

The manipulation of data in different space, retrieving the space of the brain inside the scanner is considered foundational to ‘modern’ or ‘mature’ PET technology. Specifically, PET III is often referred to as the first of ‘modern’ PET scanners, because it used coincidence detection and reconstruction algorithms based on the algorithms developed for CT by Hounsfield, and Cormack in 1972. In order to be able to measure “in 4-D” therefore, the relation between the space of the brain inside the scanner and the space of the digital image had to be constructed. Representations in PET imaging are the product of the recovery of the origin in space of the signal, and this is built into the scanning technology. “Tomography, the technological possibility of making these kinds of images, is also the key to placing brain activity in space.

A further line of argument also corroborates the significance for functional imaging’s contributions of having a spatial dimension: new technologies, such as MEG, and older ones ERP/EEG have been enrolled as part of the armamentarium of functional imaging in the early nineties, on the basis of the spatial information they could convey. This shift is visible in descriptions of the technologies, in editorials, or articles which review functional imaging. This is due, in part to developments in modelling that allowed better attribution of the source of the signal (Wood, 1994) and in an increased the number of sensors (from 12-20 sensors to arrays of 120-150). This resulted in a better link of the activations to specific sites; the source of the signal is less uncertain than before, when different types of activations could have been responsible for the same detected pattern (Mountcastle, 1998). For example, the EEG/MEG were added to the ‘subtitled list’ of technologies of the Journal of Neuroimaging in 1994, stressing that they were now able to contribute to the study of human cognition and perception as well as clinical use because they could be made spatially relevant. The notion of space is determinant: MEG “is treated as a brain imaging technique rather than as a type of ERP recording because

---

125 Developments in computer power are also sometimes mentioned, although as is often the case in these types of histories, the reliance on computational power, a technical feat, is backgrounded in favour of the intellectual advances allowing image reconstruction.

126 The current form of PET scans is also traced back to the constitution of a ‘functional image’ (Dumit, 1995).

127 Andreassen (1988) lists SPECT, CT, MRI, and PET; by the mid-nineties, the oral sessions of the Conference on Functional Mapping of the Human Brain consciously aim to include studies done with techniques such as MEG and to include EEG and MEG in the ‘short course’ offered to attendees.
most recent MEG methods provide a ‘map’ of activity over the whole cortex. (Hugdahl, 1995).“

As these technologies provide spatial data, they come to be considered as part of the brain mapping ‘box of tools’. This association tells of the centrality of spatial information of functional imaging technology. Tools are appropriate if they can provide data about the brain in such a way that they can be represented in space—precisely as ‘measurements laid out over space’.

If PET provided tomographic data, having data represented in a physiologic space was not meaningful. The need to create a special space in which to understand PET was an important item on the agenda of the growing PET community in the early eighties. Without repeating all the arguments made in chapter 2, it is useful to note that the spatiality of PET measurements has long been a core concern. PET was said to present “a challenge to an old discipline”. It provided physiological measurements in the space of the brain that had to be both distinguished and reconciled to the anatomical space of the brain. The physiological space was eventually constructed so that it could be layered onto an anatomical space: representations in 4-d are the product of PET methodology and technology, not an afterthought.

These efforts in functional imaging have resulted in technologies that produce traces in explicit spaces, and modes of analysis that rely on well-defined spatial components and anatomical referents. These are not post-hoc contextualisations of functional imaging data, but are integral to obtaining it. These elements of functional imaging are also relevant to understanding the other claims made by functional imagers. The pictorial and spatial aspects of anatomical imaging technologies are also found in the construction of PET scanners and their interpretation.

Trope 4 Concreteness of Scans

“For functional specialisation, every guess was that there was some specialisation. It came as no surprise that you would get these little patches when you stimulated people with motion or colour, there was no great paradigm shift, but by virtue that it was clearly evident, that you could see the functional specialisation in action, it suddenly acquired a concrete status that it didn’t have before (Senior Researcher, trained as physician).”

New evidence using functional imaging techniques provides a ‘concrete status’ to theories of brain functions. Since these studies are done in humans, the full range of the mind’s functions can be studied, and also made concrete. Specifically, many of the ‘higher cognitive functions’ are in the frontal lobes, so that animal studies are of ‘limited use’ since “the biggest discrepancies between man (sic) and animal are found in the frontal lobes (Frith et al, 1991).” Finding biological traces of mental processes and illnesses has also been proposed in cognitive psychology and psychiatry.
The normal human brain can therefore be used as a basis for those studying the mind:

"The goal of cognitive neuroscience is to identify the neural substrates of cognitive processes. Our chances of achieving this goal have radically increased during the last decade by the introduction of functional neuroimaging techniques (Cabeza and Nyberg, 1997)."

The need to link cognitive activity and the brain is a revision of the cognitive sciences agenda as discussed in chapter 3: "Those cognitive scientists interested in a deeper understanding of how the human mind works now believe that it is maximally fruitful to propose models of cognitive processes that can be assessed in neurobiological terms (Gazzaniga, 1989)." Brain imaging provides such a tool for deepening one's understanding by exploring the space of the brain. The possibility of seeing the brain provides a more scientific basis to cognitive neuroscientists:

"It is important to emphasise that cognitive neuroscientists are eclectic in their mode of experimental design and methods of execution. However, the coincidence of this new field with the appearance of new methods for imaging the workings of the human brain has established cognitive neuroscience as an important enterprise in the human brain science, one in which the mapping studies using imaging methods now coalesce (Mountcastle, 1998).

The imaging technologies provide more scientific methods in the eyes of this prominent physiologist, by apprehending the concrete brain rather than the elusive mind. Functional imagers often point out that psychologists do not deal with the brain, but with a construct they call the mind. What the functional imaging methods have to offer is a grounding in the brain of these constructs:

"It all depends if they care about where things are located in the brain. If they're cognitive psychologists, then they don't understand that all objects are in 4 dimensions, not just one. Cognitive psychologists tend to think of the mind as being only in time. But the mind has a physical counterpart, the brain. And if you want to adequately study the mind, you need to study the brain as well. And that moves you into four dimensions, and that means you actually represent where the properties are in those three dimensions, and that you need to study them, in space, over time, and that is a shortcoming of theirs (Senior Researcher, trained as physician)."

The brain as a space in which/through which the mind is to be studied is overlooked by psychologists, focused as they are on 'process', in terms of time, and not on the 'implementation of these processes'.
The way in which the mind is made concrete through being studied with functional imaging again focuses on the use of elements of the anatomical tradition. The subtraction method based on Donders’ work is adapted here so as to be the measurement of activity laid out in space. The contrast between the tasks represents a particular ‘operation’. The operation is then considered to be implemented in the area (or areas) that differ.\textsuperscript{128}

It becomes clear why the adaptation of the Donders method from time to space is determinant in translating much of the phenomena of cognitive psychology into phenomena that can be studied with functional imaging. This experimental approach has been rather inelegantly formulated as the ‘where’ question. Thus, ‘where’ has been described as the question about the human brain best answered by brain mapping’s converging disciplines (Wood, 1994). But ‘where’ has not always been the key question for cognitive psychology, (Posner and Raichle, 1998). “The particular contribution that functional imaging provides is to penetrate the brain space and allow the study of the mind in that space rather than treating it as a series of events in time (represented as a series of boxes).

“...the critical thing about non-invasive techniques are one, you can investigate and measure human brain function in life. There is no other way of doing that, other than by pencil and paper, talking tests. But that sort of testing doesn’t actually tell you anything about how brain function is implemented in the material substance of the brain. It tells you nothing about which areas of the brain are involved, how their activity’s integrated, what the substrate for these brain functions is (Senior Researcher, trained as physician).”

Representations make this argument very powerfully, since they render mental phenomena measurable, and place them in space. Contrasting approaches in neuropsychology and imaging, this respondent highlights the concreteness of using representations and links it to its visualisation:

“It’s really boring to get up there and say, well, I have this patient and he has a lesion in the brain here and he can’t do this task, or just get into this little nitty gritty detail about a particular cognitive function of interest—cognitive function of interest are thought about in an abstract level and are not easily visualised.....Most phenomena in psychology you cannot see (Junior Researcher, trained as psychologist).

\textsuperscript{128} For those conversant with this particular methodology and the critiques often levied against it, the assumption of ‘pure insertion’ (that tasks can be considered as independent building blocks, and hierarchically ordered in an increasingly complex task in an experiment) is also reproached to functional imaging. Because of the shift to a ‘visuo-spatial’ mode of measurement, however, the case is made that if the brain begins to use a different strategy altogether rather than ‘linearly’ recruiting more areas, this will be ‘visible’ to the experimenter; the assumption can be checked.
Another psychologist recounted the experience of going to psychology conferences and “having people come up to you and say, ‘wow, you’ve got a brain on your poster’” (Junior Researcher, trained as psychologist). Measurement laid out in space does count.

Accusations of a lack of sophistication in manipulating the ‘function’ being studied have been made by some cognitive psychologists (as noted in the discussion of ‘pretty pictures’ above). But the measurements of cognitive scientists are less ‘direct’, to the imagers:

“by observing the input and output responses, … they are not able to demonstrate the mechanisms by which the organ works. This is formalistic, whatever boxes they put in. These boxes are not ontologically committed, so that’s a major drawback. (Senior Researcher, trained as neuroscientist)

Because based on external measurements (reaction-time or accuracy of responses), cognitive psychologists can only provide an indirect measure—indirect, in the sense that it will not measure activity in the space of the brain. Pinker makes this contrast between psychological experiments and imaging work:

“More generally, I wonder whether PET research so far has taken the methods of experimental psychology too seriously. In standard psychology we need to have the subject do some task with an externalisable yes-or-no answer so that we have some reaction times and error rates to analyse—those are our only data. But with neuroimaging you’re looking at the brain directly so you literally don’t need the button-press or the overt blurring (Pinker, 1994).”

The concreteness of measuring mind phenomena in the brain also led this researcher to use PET. He had been working in a group where he was at the ‘top-end’, the mind end, while his colleagues were more biologically-oriented researchers. Imaging provided the possibility of ‘testing’, of finding a physical basis to his ‘boxes’:

“…. And I produced various theories about how hallucinations or whatever might relate to brain functions or whatever. But of course it was impossible to test them at that time. And there were a series of lucky coincidences. in that in 1988, the first thing that came out in Nature and Science almost at the same time, by Posner and Raichle and others, where they used PET, specifically to look at cognitive components of language. And up to that time I hadn’t read anything about it. But this was directly taking a cognitive psychological model with all these boxes, as I’m sure you know, with all the arrows, saying this box is in this bit of the brain, and we’re able to determine this by doing PET scans. So I was obviously very excited about this, because my work was full of these boxes and I had thought in this case I can find out whether the boxes exist and where they are. (Senior Researcher, trained as psychologist)”
Functional brain imaging is therefore the constitution of spaces for measurements and measurement of activations in relation to those spaces. While the point may not be about how the pictures look, it is very much about seeing the activity being laid out in four dimensions. Showing that mental processes are somewhere in the brain relies on the technologies and methodologies of space reconstruction of PET and the subtraction method. By making and showing their measurements in the brain based on spatial differentials, the anatomical level must be rendered, reintroducing the pictorial in the representations of functional imagers.

**Trope 5 Seeing the Entire brain**

“... you find a brain correlate, namely change in blood flow. Of course, compared with EEG, it's a better correlate. It's better defined spatially, and it covers the entire brain (Senior Researcher, trained as neuroscientist).”

Another distinctive claim of functional imaging is the possibility of imaging the entire brain. This has implications for demarcating imaging work from both neuroscientific approaches and neuropsychological studies, which have been concerned with localisation or mapping work (in the general sense of attributing functions to locations). Being able to measure the entire brain is used to contrast functional imaging with other modes of measuring the brain. Other methods make 'one small measurement', by 'probing' the brain as described above, whereas functional imaging can encompass the entire brain.

The apprehension of the brain in its entirety provides a different territory for investigation than the space of the brain that is available to other methods, such as intra-operative stimulation, where only a very small part of the brain is visible and manipulable. Since localisation research is the coupling of function and location, a different version of a territory leads to different definitions of functions. The possibility of measuring all processes in the entire brain subtends the claims of functional imaging that it can investigate the brain at a 'systems level'. This argument is often used to show the break between the localisationists of the 19th century and functional imaging. Since they do not equate one region with one function, systems-levels investigations mark this type of mapping as a new endeavour. Thus, in contrast to traditional methods of neuropsychology or intra-operative stimulation, functional imaging does not show only the essential areas for a function, but an entire system that subtends a function. Measuring activity in the brain at a 'systems level' has been an important result of collaborations of psychologists and neuroscientists:

125
"First, as you know, the results are bound by the methods. So if you work with single unit recordings, you tend to be short-sighted, you will understand some details of local computations, but you have no idea whatsoever, how the organ is functioning at the systems level. Nobody had any ideas about the function at the systems level...and one of the major landmarks is this immense, we can call it parallel processing, but we call it multiple neuronal populations or multiple synaptic populations collaborate to produce functions of the brain....[neuropsychologists] tend to interpret their results in the traditional localisationistic way. They had no idea how dispersed, I wouldn't say diffuse, but dispersed it really is...the brain really does work this way with these huge populations. So I think that's very fortunate. That is why the methods are so efficient. (Senior Researcher, trained as neuroscientist). “

According to this pioneer of functional imaging, without being able to measure these entire systems spread all over the brain, the way the brain works could not be understood. Being able to consider functions as systems, (and not as 'unitary', with particular places in the brain, which once removed will affect only that one function leaving the rest of the brain undisturbed), is “a major methodological leap, a change of mindset.” Functional imaging also claims that it will inform physiologists about where to place their recording devices. Such claims of measuring the simultaneity of activations of parts of the brain, of measuring at the systems levels relies on detecting groups of areas connected in space and the layering of functional and anatomical information.  

Thus, in spite of the distantiation from imaging and the visual discussed in the first part, the arguments and claims of functional imagers rely to a great extent on aspects of representations from these traditions. In this section, I have examined a number of 'redefinitions' in relation to functional imaging. What constituted a 'modern' PET scanner, what makes a technology a functional imaging technology, what constituted a proper basis for analysing PET data. The answers to these questions have to do with the possibility of providing spatial measurements. Linked to these modes of measurements are the particular knowledge claims that have arisen from functional imaging: seeing the brain at a systems level, making mind phenomena visible in the brain. These claims which set functional imaging apart from other approaches and other groups of investigators are linked to the representations of functional data in a dimensional space:

---

In relation to neurophysiology, there are problems about knowing where to place the electrode to sample brain activity. Note how the common element of space may enable communication across these techniques.

Not surprisingly, if psychologists and cognitive scientists question the notion of ‘function’ that is used in these studies, neuroscientists’ criticisms come from the brain end. They challenge the meaning of the signals detected by PET. Here too, hierarchies of evidence are at play. Recent pronouncements on the foundational principles of neuroscience state that the ultimate cause of mental activity is the neuron—so people doing EEG measurements see imaging as very indirect, because blood flow is coupled, but sometimes loosely so, to the activity of neurons. Researchers dealing with measurements of neuronal activity are sometimes critical of imaging. One researcher who had moved from research using EEG to imaging described going from ‘evidence to suggestion’, from physiology to metabolism. The link between neuronal activity and blood flow has been a controversial topic in the imaging community.
the pictorial conventions of anatomical knowledge are mobilised to relate functional data
to the substance of the brain.

Mixed traditions, Hybrid Objects

After about ten years of functional imaging research, there have recently been
calls to review the research agenda. Interestingly, many of the criticisms of the current
state of research and proposals for future developments also point to the place given to
representations in functional imaging. The results provided by functional imaging have
been labelled as limited, because ‘geographic’ (Mountcastle, 1998). While the
‘neophrenology’ of the past years has been necessary, and continues to provide unique
insight (into the entire, normal living human brain...), researchers need to consider it as
an empirical basis and not as an end in itself (Frackowiak, 1998b). Knowing the answer
to ‘where’ should be used to answer questions about ‘how’ the brain works. These
representations should be used as the empirical basis of further analysis; as observations
on the basis of which researchers can theorise; as the materials from which ‘principles’ of
brain organisation will be discovered. Maps will lead to principles and to models of brain
function.131 As one researcher predicted: “So once the field grows up becomes less
interested in mapping, it will be numbers (Senior Researcher, trained as psychologist)”. Such statements makes sense in terms of the scientific hierarchy of evidence with which
this chapter began, and which was shown to be embraced by the researchers using
imaging. Accordingly, functional imaging aspires to scientific status; an empirical basis is
built; as a field matures, the representations used will be purified and tend towards the
quantitative. This may be yet another rejection of the visual, to discover by non-visual
means what is “hidden beyond the phenomenal tide” (Stafford, 1991). If the current
research agenda is transformed to address other questions about the brain, the style of
empirics will also change, the importance of representations will be altered.

Others predict that future development is possible for brain mappers, although

“the acceptance of brain mapping data, either from an individual modality or
provided in composite, will be enhanced by display approaches that provide data
presentations and images that are immediately recognisable to individuals with a
knowledge of cerebral anatomy (Mazziotta and Toga, 1994).”

Data will have to be translated into a form that allows a visual understanding, the
immediate, clinical, image-based use. If the results of research are to be ‘applied’,
representations will have to be adapted to a different understanding—the measurements
of scientists will have to be brought more closely in line with the anatomical tradition of
the clinic.

I have analysed here the complex understanding of representations by functional
imagers in terms of the demarcation of a new approach to the study of the brain. As seen

131 See for example “Principles or Maps” (Friston,1998).
in the first part of this chapter, the work done using representations is defined as scientific and quantitative, the making of measurements. These measurements can be 'visualised', but they are not constituted nor are they understood as images, as pictorial representations. Researchers distinguish their work from that of the visual detection of the clinic by insisting on defining their work as quantitative measurements. Representations may play a useful, communicative role, but they are not determinant in the work pursued.

In the second part, I examined how other kinds of distinctions between how imagers see their work and that of others are made. By constructing their practice as dealing with the activity of the mind, and showing this activity in space (directly, at a systems level and in normal brains), the functional imagers define an approach that is very much bound up with the use of representations. Researchers prefer to define their work as measurements, which are the results of manipulation and experimentation. But the very constitution of these experiments is based on the possibility of representing data in space, and layering the activity of the mind onto the brain.

Making 'images of mind' in a bounded brain provides a basis for biological explanations of behaviour. Functional imaging research has been directed at finding the physical substrates of mind, and the underlying causes of deviant behaviour and disease. In some ways, this project is comparable to the phrenological and localisationist projects of the nineteenth century, where faculties were linked to bumps and pathological functions to brain regions. But brain mapping is constructed as measuring activity in the complex space of the living, acting brain, rejecting both the shallow study of surface of phrenology, and the anatomo-clinical stance of the localisationists' post-mortem correlation.

At the heart of the paradoxical understanding of representations in this field is the dual appeal to the graphical and pictorial. Functional imaging makes use of the pictorial tradition of anatomical representations, to provide spatial referents to the data it produces (activity in the brain) and convey the notion of control of the space of measurement (seeing the entire brain). Yet it also distantiates itself from the traditional visual understanding that accompanies these anatomical representations, and invokes a graphical tradition where the correspondence of image to world is one of quantity and measurement, not one of depiction. The functional imagers' hybrid object of the mind in the brain is constituted by the juxtaposition of hybrid representational traditions.

By observing the hopes and anxieties around representations, this analysis reveals important dynamics in the constitution of a scientific, research-oriented project. What constitutes relevant empirical strategies are deeply rooted in material, disciplinary and institutional contexts from which this new project arises. Numerous case-studies have shown that all sciences deal with signs, and that differences in 'epistemic cultures' (Knorr-Cetina, 1996) or traditions (Galison, 1997) can be observed. This chapter shows that cultures can also clash, and that seemingly contradictory statements are in fact sensible in highly specific, hybrid contexts-- the repercussions of empirical dissonance (image/number). Galison has suggested that new forms of imaging, using computerised
counters which turn numbers into images, has marked the integration of traditions of evidence in physics:

"the tension between analog technical knowledge and digital technical knowledge is a deep one and that this division has cut across disciplinary boundaries. The weaving together of the two traditions in the last few decades represents a previously hidden unifying trend in an age of scientific specialisation. Homologous and homomorphic representations have coalesced." (Galison, 1997)."

The case of functional brain imaging shows rather that, while kinds of knowledge have been integrated to some degree, and reshaped to some extent, differences do endure. This may be because Galison’s case examines these traditions within a lab situation. Functional imaging has had a much less structured environment, so that different traditions of evidence live on in the clinic and in the various places of work involved, challenging and destabilising these attempts at syncretism. While the use of images seems to be increasing, the intersection of the visual and digital culture implies a redefinition of the visual, especially when understood as 'pictorial.' The new quantitative anatomy constitutes an important example of such redefinitions.

Furthermore, this attention to the empirics of brain mappers not only makes sense of the rejection of the clinical visual diagnosis discussed in the first part, but it also explains the particular version of anatomy developed by brain mappers (the many permutations of the x, y, z Talairach brain space). Functional imagers do not value the skills of recognition of the neuro-anatomists or pictorial evidence, and instead invest the space of the brain with a graphical efficacy that allows quantitation and calculation.

This analysis also makes sense of the ambiguous relationship of researchers to the representations they use, and proposes that this relationship is the result of the aspirations of brain imagers in terms of scientific credibility on the one hand and on the other, of the ways in which they carve out a terrain of particular expertise in relation to other disciplines. These two elements can be shown to sustain both an iconoclastic stance towards these representations, while also providing motivations for the sustained use of representations.

The paradox of images in functional imaging results in the attempt to segregate various aspects of representations. Hence researchers separate the visual appearance from the content, seeing from reasoning, imaging from experimenting, yet rely on the synthetic power of representations to make their object, and to inscribe new phenomena in the space of the brain. While efficiently evoking control and knowledge of space and simultaneity of measurement, representations must be used with care and cannot simply be presented as visual proofs, without endangering claims to scientific status. Even in non-scientific contexts, the visual argument must be used circumspectly. The technological feasibility of visualisation is at least partly shaped by existing scientific criteria of validity and acceptability of evidence. The next chapter will consider digital
tools and imaging databases, and will show how new objects can and do arise in a context where the quantitative image is the starting point.
Chapter 5 Atlsing the Brain

New Approaches, New Atlases, New Authoritative Standards

A recent textbook on brain mapping announces: "...databases will develop in which N-dimensional attribute lists will exist for each voxel in the human brain." Voxel, a neologism derived from the slightly older pixel (picture element), are then to be found in the brain. In a certain context, yes... This prediction of forthcoming total knowledge about the brain refers to the building of a new wave of digital atlases, since the late eighties. These atlases, it is predicted, will contain any number of types of data (n-dimensions) and will be integrated in a digital tool (as voxels). Any kind of information, be it physiological or anatomical, can therefore be attributed to a particular voxel in the brain, all data being translatable into a similar format. This approach constitutes an important shift in neuroscience, where types of data (be they measurements of electrical activity, of cell-types, of sizes of structures, of chemical activity) about the brain have been the province of particular sub-disciplines, and gathered in particular formats (drawings, quantitative measurements, individual maps, scans). Yet, in these new tools, these various types of knowledge are being juxtaposed and integrated into large digital tools.

In part, the new atlases have been developed in response to the needs of existing research streams in the brain mapping community. But this new development in neuroscience has also been significantly shaped by the support of the Human Brain Project (HBP), a large-scale initiative developed as part of the American Decade of the Brain. The HBP proposed guidelines for a neuroinformatics approach to the study of the brain, that is to say, research involving the use of informatics for pursuing neuroscience. This has meant the active integration of digital and electronic tools in research and a centralised coordination of these efforts. This chapter will examine how this approach has led to the creation of a new kind of representation for neuroscience, a virtual brain, by tracing how these new atlases are constituted, the accompanying changes

---

113 From Human Brain Mapping: the Methods, (Toga and Mazziotta, 1996)
111 This term is first mentioned in relation to the BMP in Addendum, September 15 1994, to Programme Announcement published in NIH Guide, vol. 22, April 1993. The term was already in use in 'computational neuroscience'. Making 'images of mind' in a bounded brain provides a basis for biological explanations of behaviour. Functional imaging research has been directed at finding the physical substrates of mind, and the underlying causes of deviant behaviour and disease. In some ways, this project is comparable to the phrenological and localisationist projects of the nineteenth century, where faculties were linked to bumps and pathological functions to brain regions. But brain mapping is constructed as measuring activity in the complex space of the living, acting brain, rejecting both the shallow study of surface of phrenology, and the anatomo-clinical stance of the localisationists’ post-mortem correlation.
to the features of the brain included in these atlases, and the new applications that have been built into these tools.

This development is important in that it intersects with the growth of brain imaging with which this thesis is concerned. But, furthermore, the case of neuroinformatics will provide the opportunity to examine the use of digital and electronic resources in scientific research. Neuroinformatics are more than simply the greater use of computers, more than computerisation of existing processes and standards, but rather might represent a particular configuration of goals and practices around a new kind of digital and electronic scientific representation. These might also be found in other scientific endeavours: neuroscientists were not the only ones addressing the need or desirability to develop databases and electronic resources around the turn of the decade. Other communities (environmental science in US, Genome, climate change) were also considering the usefulness of such tools, and the topic of ‘collaboratories’ as a radically new way of pursuing science was arising in the American Federal research management context. New tools have also been developed in medicine, including expert systems for medical diagnosis, digital anatomical atlases and databases (VoxelMan, Visible Human) and repositories for meta-analysis (Cochrane Initiative).

A second and closely related line of analysis will run through this chapter, and concerns the normative role of these atlases based on voxelised, virtual brains. Atlases, be they geographical or medical, have traditionally been used as educational aids and as reference works (Tufts, 1983; Wood, 1993). These new atlases will not only contain many types of data, but this data will also be qualified to represent the normal human brain. As these new atlases take on a new digital form and are built to contain many types of information, they also become differently authoritative. The second argument will therefore link changing knowledge about the brain with changing notions of the normal brain. In the course of developing a technologically-supported basis for integrating knowledge, the ‘normal’ is translated into a new context and undergoes significant transformations. This level of analysis will serve to highlight the shifting empirical and epistemic contexts in which neuroscientists work, while also being significant as a phenomenon affecting clinical procedures and therefore every potential recipient of neurological, neuro-surgical, psychiatric or psychological care.

What is ‘normal’ in the Decade of the Brain?

The analysis of the new atlases proposed in this chapter relies on the mutually constitutive dynamic of modes of measurement and normality. What is worth measuring and the manner in which it is measured are related to what is worth evaluating as being normal or not. This link is especially visible in atlases, since one of the conventional features of an atlas is its authoritative status (Wood, 1993). Atlases are normative in the sense that they are used to define, to diagnose, to label, to educate about a case, in relation to a chosen definition of the normal. As a normative representation, the atlas is a complex
entity, a key link between description and prescription—just like “normal”, a word that
dances on the border between fact and value, how things are and how things ought to be.
to paraphrase Hacking (Hacking, 1990). The determination of normality is an important
aspect of medical research and practice and has been analysed as a key concept in
providing therapeutic goals and prescribing types of interventions to be performed
(Canguilhem 1978; Hiddinga, 1995; Waldby, 1996a). In order to understand the normal,
one must understand the constitution of the norm:

“normative in philosophy means every judgement which evaluates or qualifies a
fact in relation to a norm, but this mode of judgement is essentially subordinate to
that which establishes norms. Normative, in the fullest sense, is that which
establishes norms (Canguilhem, 1978).”

This applies not only to medical work, but also to research endeavours and to
representation of objects of research. Lynch has highlighted how this process is also
central to laboratory work:

“mathematical and graphical facilities are implicated in the very organisation of
what the specimen consists of as a scientific object. The details of laboratory
work, and of the visible production of such work, are largely organised around the
practical tasks of constituting and ‘framing’ a phenomenon so that it can be
measured and mathematically described (Lynch, 1990).”

Thus, in order to understand the atlases as normative tools, it is necessary to retrieve the
conventions that have been selected to enable measurement. The power of these
conventions resides in the seamlessness that can be achieved, and I would argue that the
atlases that work best are those where various conventions mutually reinforce each other.
For the sake of analysis, however, three types of conventions will be distinguished here,
regarding the selection of representative objects, the measures taken to ensure objective
findings, and the features of interest included in the atlases. These conventions will be
used to discuss the constitution of digital atlases representing three versions of the
normal: the average, the probabilistic and the probabilistic-variable (diagnostic).

Sampling

One of the important conventions that will be considered in this analysis is the notion of a
‘kind’, a set of cases that can be measured and compared. This convention will be
explored in analysing how a sample is selected, as representative of a normal population.
A number of traits are usually invoked to make up these categories, pointing to an endless
regress to earlier conventions, as Canguilhem has noted. The traits that are selected mark
the body, in the sense of pointing out and showing what makes certain bodies possibly
‘other’. Historically, these have been woman, the colonised, the slave, the worker, “other
to the fictive, rational self of universal, and so unmarked species man, a coherent subject.
(Haraway, 1991).” The construction of this and other subjects has been amply shown in
feminist scholarship. The involvement of atlases in this process has been analysed in terms of the young male body as the norm, and the female or ageing body as the deviating version (Lawrence and Bendixen, 1992). In the atlases of the brain considered here, samples are variously constituted, along a number of traits. This selection is significant because it shapes the differences in measurements that will be obtained: if men and women are constituted as different kinds, then measurements can be contrasted in terms of these traits of the sample.

"...enumeration requires categorisation and ... defining new classes of people for the purpose of statistics has consequences for the way we conceive of others and think about our own possibilities and potentialities (Hacking, 1990)."

A further related issue in the selection of a sample is "the problem of 'representativity' of the anatomical image, its claim to be typical of a class of phenomena (Waldby, 1996a). " I take this component, and the further possibility of applying a representation to a group, to be different from the objectivity or accuracy of an image. The lack of a term for this epistemic trick played by the atlas highlights the significance of eliding the representational work performed by the atlas. To posit a gap between what is selected to be represented, and the population to which it might be applied is to call into question the possibility of using representations in realistic terms.

Objectivity

Another set of conventions in the making of atlases concerns their status as scientific tools. As normative instruments, atlases rely on the objectivity invoked in their constitution, and as such are always carefully (though not always explicitly) selective in order to be objective (Daston and Galison, 1992). The removal of the subjective provides protection against imposing esthetic, moral or theoretical elements on the phenomenon studied. Daston and Galison identify three basic modes of objectivity (effectively, three modes of representation) in the (paper) atlases they survey: the ideal (perfect, unblemished), the characteristic (showing a typical case) and the individual (Daston and Galison, 1992). In each case, elements of 'raw nature are selected and represented. The selection involved can be that of an expert whose judgement is trusted, and whose name is often borne by the atlas. Such atlases can be found in anatomy, for example Vesalius'..."
De Fabrica, or in neuro-anatomy, Brodmann's or Talairach's atlases. Alternately, the ideal of selection of an atlas can be based on mechanical objectivity (Daston and Galison, 1992), where that very embodied judgement is restrained and delegated to a technology, such as the camera, or the brain scanner. This last mode will be shown to be part of the making of brain atlases, through the use of the automated representational power of imaging technologies.

Before discussing the new brain atlases, two more elements, not raised by Daston and Galison, must be noted. Their absence from the discussion of paper atlases is at least partly due to the fact that they grow in prominence when atlases are in a digital format. First, along with mechanical objectivity warranted by scanning and imaging technologies, these atlases are constituted through the mobilisation of computer-supported statistical and quantitative apparatus, which provide a further mechanism for validation. The second feature defines the use of the atlas. The scientist wishing to use the atlas must infer from the representations it contains, and relate what is learned to the individual specimen encountered (Daston and Galison, 1992). While Daston and Galison do not describe this process explicitly, they do seem to assume that it is mental, probably acquired as part of a learning process. In the case of these atlases, the objectivity built into the atlas also concerns its application; ideally, individual data are to be automatically compared to the representations in the atlas, a process also supported by a statistical and quantitative logic. These elements, which might be constitutive of a new digital objectivity, will be discussed in the conclusions.

Features

Atlases, like maps discussed in chapter 3, emphasise particular features of an object of study. In these atlases, a number of new features will be shown to arise in relation to new modes of measurement and new technologies. These atlases mark a new focus on the human cortex, and its variability, both in anatomical and functional terms. As well, the analysis of volumes in the brain, 'density' of tissues and relations between amounts of substance (grey/white/ventricles), while not entirely new to neuroscience, receive much more attention in these atlases. Other notions, such as variability, population and probabilistic anatomy are also recast in these atlases, as the uses of the atlas are defined by neuroinformatics.

The 'normal', defined objectively, is therefore not a monolithic concept but is rather dependent on the institutions, technologies and kinds of measurements made (Hacking, 1995; Sekula, 1986). Atlases are representations created through (and

---

137 Pasveer (1989) describes this process as a socially constructed (non-cognitive) process of meaning-making, where context and content are only progressively shaped as (separate) entities.

138 Many other transformations of scientific work have also been linked to the use of electronic highways and digital models and databases: the reconfigurations of research practices, authorship, intellectual property, patterns of collaboration, etc. etc. See for example Fujimura and Fortun (1996) on the use of genetic databases versus 'wet' experiments in the lab, and the respective amount of 'labour' involved. These cannot all be addressed here and constitute other avenues for exploring changes in scientific activity (but see NIWI, 2000).
sustaining) these conventions and will serve to highlight key features of neuroinformatics. From this point, the proceeds as follows; Neuroinformatics and the research context of the Decade of the brain are sketched. The importance of standardisation, integration and translatability (the ideals of the HBP) through digitalisation and automation are shown to be significant forces that shape ‘normality’ in these atlases. Finally, the implications of digital and computerised resources for new notions of objectivity, atlases and diagnostics are drawn out.

Brain Imaging and Brain Mapping Precursors

Neuroinformatics atlases were built by drawing partly on existing research in the imaging community. As discussed in earlier chapters, the need for new atlases of the brain was discussed before the instigation of the Human Brain Project. Brain mapping research had been the context of new applications of traditional paper atlases, especially that of Talairach. There was already a number of efforts to improve on the contents of the atlases, and to improve and standardise the way a given case would be compared to the atlas. There was also research into digital spaces in which to make these comparisons (chapter 2). Functional imaging, especially with PET, was articulated as an approach that required correlation to anatomical data. Various methods of correlation were proposed in the course of the eighties, from head holders used to correlate scans for a single subject between two imaging technologies (pet and CT or MRI), to head holders that could be used to relate scans between subjects, to more complex computerised methods for linking functional activity to anatomy. For the PET community, developing better atlases was seen as a way of reinforcing PET results, and the suggestion to develop MRI atlases was taken up as a resolution of a series of workshops held in the eighties (1984, 1987). There had also been criticisms directed at brain mapping experiments, challenging the research methods and especially efforts at localisation. Errors in localisation of activations and subsequent retractions and corrections created the feeling among researchers that the credibility of functional imaging was at stake and that more objective modes of analysis might help solve this. The workshops for standardisation of PET analysis was noted by the report of the Institute of Medicine as having achieved some progress in addressing the issue of common standards (BrainMap is specifically mentioned), as a successful example for the rest of neuroscience. Neuroimaging technologies had also been spreading rapidly in the course of the eighties.139 The possibility of imaging the normal human brain was especially significant because unlike that of animals who could more easily be dissected, human brain were much more scarcely available for post-mortem dissections (Crick, 1993) and require extensive work on the part of neuro-anatomists and their medical colleagues (Prins, 1998). Brain mapping had also focused attention on the cortex as being the object of a new kind of brain localisation research (chapter 3). The cortex was considered highly variable but also highly significant—whereas lower-order areas give

139 CT was already contributing to the exploration of theories of anatomical difference and hemispheric dominance in the seventies. See Galaburda et al (1978).
robust signal, higher order areas would produce more subtle activations.\textsuperscript{140} This is therefore the context in which the HBP was emerging.

The Agendas of the Decades of the Brain, Neuroinformatics, and the Human Brain Project

The atlases that have been produced in the course of the nineties, sponsored by the HBP, are complex tools meant to answer needs beyond those of improved localisation that were arising in the imaging and mapping community in the eighties. The atlases acquired other functions as they became part of larger agendas, such as those of the Decade of the Brain and of the Human Brain Project.

The nineties were declared the Decade of the Brain by a number of governments. Japan led (in the late eighties) the development of the ‘Human Frontier Program’, which strongly emphasised neuroscience research. The United States also dedicated the decade (in 1990) while the European Union launched its initiative in 1992 (Pandolfi, 1993). A number of other countries (Italy, Sweden, The Netherlands,\textsuperscript{143} Canada) also launched similar initiatives around this time. While thematically linked, the agendas of each initiative differed in several ways. The goals formulated by the European task force for the Decade of Brain Research addressed the need for neuroscience to “reach a ‘critical mass’ of neuroscientists needed to carry out research most efficiently” and be able to compete with the US (Abbott, 1992; Pandolfi, 1993; Mendelvitcz, 1993).

In the United States, the state of neuroscience was celebrated, and the worries that were voiced about it did not focus on the ‘brain drain’ issues of European policy-makers and their need for a critical mass of research and researchers, but rather on the fact that neuroscience was becoming critically massive. The state of neuroscience and its recent rapid progress were attributed to advances in molecular biology, imaging, neurobiology, and computational power.\textsuperscript{142} While noting that the successes of neurosciences rightly warranted public attention and recognition, neuroscientists and policy-makers also worried that the wealth of available data was becoming the source of a crisis in neuroscience.\textsuperscript{143}

\textsuperscript{140} “Intersubject averaging requires highly accurate anatomical standardization, capable of correcting for individual differences in slice orientation, brain size and shape. For this, a method of stereotaxic anatomical localization specifically defined for use with PET was used (Fox et al. 1988).”

\textsuperscript{141} The Dutch initiative was called Hersenwerk 2002, and was launched at end of 1992, after conference in Amsterdam sponsored by the KNAW and NWO. Hersenwerk fit in well with the medical research policy at the time, with a greater emphasis on chronic illness, and a shift away from deadly diseases (Enserink, 1993).


\textsuperscript{143} The American House Joint resolutions (signed by G. Bush) declaring the nineties the Decade of the Brain noted the centrality of neuroscience for solving issues of concern to American Society, from drug dependency to the protection of “pre-born children”. (House joint Resolutions-174, 101 Congress).
This crisis was defined as an “explosion of data”, or a flood, deluge, glut of information, avalanche, overload, and so on. The following scenario articulated by Bloom (1990) was often cited, echoed or paraphrased in the following manner:

“Brain and behavioural research has exploded in the past 2 decades because of the conceptual links that were made across different species, levels of biological organisation and methodological approaches and links that were made internationally.”

But this has led to specialisation and decreased ability to relate to other findings:

“Thus, an overload of information is threatening the very fuel that has driven brain and behavioural research to the forefront of science (Huerta and Koslow, 1996).”

This crisis affected both the individual researchers, and the field, and various kinds of solutions were proposed to solve the crisis. The solutions that dominated involved the use of digital and electronic tools in neuroscience—neuroinformatics. This proposal for the use of computers had been made repeatedly, in the seventies, eighties and throughout the nineties too (Bloom, 1995; Huerta et al., 1993; Cox, 1997). But it is a view that seemed to appeal particularly at the end of the eighties, when plans for new resources for the neurosciences were elaborated under the aegis of a number of Federal agencies in the US.

In preparation for the Decade of the brain launch, a number of reports had been commissioned. One of these was sponsored by the National Institute of Mental Health and authored by Stephen Koslow (1989). The report addressed the development of a ‘National Neural Circuitry Database’, an idea that was originally proposed in the late seventies but abandoned because of a lack of technological means to achieve it (Huerta et al., 1993) and lack of consensus about the features to be included (Cox, 1997). Following Koslow’s report, a committee was set up by the NIM to address the “feasibility and utility of incorporating computer technology into the basic and clinical neurosciences in order to enhance research progress” (Pechura and Martin, 1991). In the course of these discussions, the creation of databases and other resources came to be seen, by the participating agencies and the scientists consulted, as the best and as perhaps the only way

---

144 Various versions of this narrative can be found in Bloom (1996), Jacobs (1996), the Announcement of HBP (1993), Fox (1993), and Gibbons (1992). This explosion is often illustrated by tracing the membership of the Society for Neuroscience: less than 400 scientists at a meeting in early seventies, then 20 000 in 1991 (Judd, 1993).

145 The narrative of the ‘crisis’ constitutes an interesting contrast to that of the Human Genome Project, where the narrative, as told in Mapping our Genes (Wingerson, 1990) and in the Human Genome News is one of “individual scientists gradually becoming aware of the surplus value of their combined efforts”, as analysed by van Dijck (1995). This way of making sense of a coordinated effort makes the project less urgent, but might also make it less threatening to scientists who fear imposed standards and control from above—fears which are often heard in discussions of the Human Brain Project. See for example Purpura (1997).
to intervene in neuroscience research and solve the crises that was threatening its progress as a field.

**Neuroinformatics Solutions**

After two years of consultations and meetings, a report appeared confirming the need to encourage the union of neuroscience with electronic and digital technological support. But the recommendations had changed from proposing a single ‘circuitry database’, to recommending the creation of a number of resources in a project to be known as the Human Brain Mapping Initiative. A single National Circuitry Database was to represent the known pathways in the brain that interconnect various regions, and this level of neuroscientific knowledge was meant to function as a ‘skeleton’ or framework for other levels of neuroscientific information. In the committee’s report, however, anatomy was seen as the best choice for a baseline (Roberts, 1991).

Around this baseline, a number of resources, encompassing a number of ‘levels’ of neuroscience (See Figure 20), were to be developed: reference databases, data banks, informal databases, national and international registries, research collaboration databases and speciality databases (Pechura and Martin, 1991). The report also identified the main information management needs of the neuroscientific community as databasing, (to relate data systematically and efficiently), and visualisation of structures in 3d, with the goal of relating the architecture of the brain to function.

“the long-term objective of developing three-dimensional computerised maps and models of the structure, functions, connectivity, pharmacology and molecular biology of humans, and monkey brain across developmental stages and reflecting both normal and diseases states (Pechura and Martin, 1991).”

In order to benefit from these new resources and their power of integration, the committee added, neuroscientists would need to cooperate in the creation of standard data formats and common languages for the various areas of the neurosciences and that this would present a major challenge (Pechura and Martin, 1991). The goals were therefore aimed at improving knowledge production through better integration.

---

146 Also indicative of the importance of functional imaging in this project was the original title in the proposal of the Committee, for a Human Brain Mapping Initiative, brain mapping being most often used as a general label for functional imaging research. The announcement of for the research program that followed used the more general term Human Brain Project, a term parallel to the Human Genome Project and perhaps more inclusive, given some neuroscientists’ resistance to the cognitive psychology bend of mapping.

147 These goals have been said by some of my informants to be so general as to be laughable. A footnote in the text of the report notes that this is to be but a starting point and that mapping the brains of further vertebrate and invertebrate species would also be valuable.

148 In 1995, a workshop on neuroinformatics was held through the US-EC Task Force on Biotechnology Research. Calls of the American-based project for “the integration of research from the molecular and cellular levels up to the system level” were echoed at this meeting (Mathiesen, 1996). On the international scene, the OECD Megascience Forum has recently endorsed a proposal from the US to establish a ‘Biological Informatics Working Group’, with neuroinformatics as one of its subgroups.
By fulfilling these needs for information management, the neuroscientific community would not only improve the pursuit of research, but also add value to this research. Specifically, the report insisted that databases would enable hypotheses to be tested with the models to be developed, that new knowledge would arise from querying the databases, and that the pursuit of ‘missing’ knowledge would be rationalised, as shortcomings would be highlighted and duplications avoided (Pechura and Martin, 1991). The neurosciences were therefore to be integrated through information technologies closely related and developed specifically for the neurosciences—a neuroinformatics solution to the exploding information which kept the sub-fields of neurosciences from working together.
The Human Brain Project

The report posited ideals of integration and rationalisation in neuroscience, to be achieved though databasing and visualisation. The scenario of an explosion of data was also put forward as a motivation for the announcement for feasibility studies (PA-93-068). The program announcements and its subsequent addendum and second version further insisted on the need for projects to involve both informatics and neuroscience components, as well as labs that were geographically distant. To allow standards to evolve and emerge out of the community, these resources were to be developed as prototypes, in a first phase of the project. In spite of the decision to fund ‘a family’ of resources, the coordinated databasing of neuroscientific data was sometimes identified as a ‘big science’ project (Frackowiak. 1998a) comparable to the physicists’ Super Collider and the Human Genome Project (Roberts. 1991; Purpura. 1997). It was apparent to both the members of the committee and to critics from the neuroscientific community that one of the main issues in creating a resource would be to obtain agreement on the kinds of investments to be made (be they on the part of funding institutions which would pool monies or of investigators who would share results) and the need for common measures and standards for data reporting. There were hopes that the neuroscientific community would be more successful than the splintered resources of the Genomic community, because of the central co-ordination of the efforts by a board representing the granting agencies, which would ensure that the various databases would be built so as to be compatible and could be “federated” (Fox and Lancaster, 1994).

I have sketched the contents of these many reports and discussions very briefly, for the sake of coherence and length of this chapter. This description should suffice to show, however, the strong embedding of atlases into large-scale research policy goals. These are wide-ranging, meant to improve neuroscience on a number of levels, from budgetary concerns (more bang for their buck) to that of the workbench (databases for checking existing data). These goals are built on an implicit assumption about scientific progress (the pieces of the puzzle model) and “the hope—that having all data in one place will shake loose new insights about how the brain works—[which is] is driving a surge of interest in neuroscience databasing (Gibbons, 1992)”. In this context, neuroinformatics broadened the scope of atlases and inscribed these tools in larger, wider agendas. The atlases which were a framework for relating data from 2 technologies (PET for ‘function’ and MRI for ‘structure’) became frameworks for integrating the various fields of neuroscience and solving the crisis defined in the reports for the Decade of the Brain. From serving as reference tools, atlases come to be defined as able to

Footnote 14: Funds of about 4-5 million were planned for the first call in 1993 (Announcement, 1993). By 1996, about 60 investigators were supported (Huerta and Koslow. 1996). Fears that all funding would be monopolized by this project were expressed at the time of the report, and since then, the project has also had to defend its ‘big science’ status (Purpura, 1997; Frackowiak, 1998a). Others have deplored that the Decade of the Brain has simply resulted in redistribution of the same funds, with less freedom (Enserink, 1993; Roberts, 1991)
"...provide a structural framework in which individual brain maps can be integrated."
pneumoencephalography, as a preparation for neuro-surgery) to the project of mapping the mind onto the brain (for interpreting the cortex, suspected of being variable, as investigated by PET, by cognitive psychologists, psychiatrists and neurologists). Shifts in location (clinic to lab), purposes (intervention to investigation), in sensitivity (very low to high resolution), in application (from individual patients to populations), in anatomical location (from structures with low variability to high) are all aspects that led to the adjustments made to the atlas. (See Figure 15, page 56). The first brain atlas developed in the HBP was meant to provide a better ‘target brain’ in the Talairach system I just described, and many of the motivations for improving on the Talairach atlas point back to the perceived shortcomings of the objectivity and sampling of this method.

The Average Brain: ICBM 305

In the late eighties, the Talairach atlas served to provide an anatomical reference for the activation data visible on PET scans. There were several attempts to improve various aspects of the atlas so that it would provide a better anatomical basis for analysing PET scans. One of the groups involved in this effort was the Brain Imaging Centre (Evans group) at the Montreal Neurological Institute. As a leading centre for neurosurgery and neuropsychology, issues of localisation were important for both research and clinical purposes. A better reference tool would enable PET activation results to better be targeted to the anatomy of a given patient or groups of subjects.

A digital brain atlas representing the average brain was developed in the late eighties by Evans et al (Evans et al. 1989, 1992). While these improvements were meant to answer the needs articulated by researchers, and of clinicians to a certain extent, the approaches developed were also closely tied to the growing availability of scanning and computer technologies. In the early nineties, the MNI joined two other groups which, in the course of the preceding decade, had also been involved in efforts to improve localisation. UCLA, the MNI, and the University of Texas Health Science Centre at San Antonio (UTHSCSA) formed the International Consortium for Brain Mapping (ICBM)\(^{151}\) formed in order to place a bid for funds in the Human Brain Project. Together, they received a grant in the first round of the Human Brain Project in 1993.\(^{152}\) These groups shared the view that standardising some aspects of PET data analysis was desirable, and all three had put forth suggestions in publications. Of these, the work of the MNI was most visibly carried over into the ICBM research agenda, as its ‘average brain’ was further developed.

Specifically, the shortcomings of the Talairach atlas were to be remedied, first by developing better algorithms for comparing brains, so that differences in size, shape and

\(^{151}\) All three centres are based in ‘medical’ settings. This may have further encouraged the use of ‘scans’ as data.

\(^{152}\) Researchers from three more institutions have joined the efforts of the Consortium to contribute specific expertise for their next program grant to be funded by the Human Brain Project (1998 to 2003): Albert Einstein College, Heinrich-Hein University of Dusseldorf, Stanford University.
position in the scanner would be overcome (See Figure 7, page 23). Second, the target brain, to which all other brains were to be related was felt to be too idiosyncratic, since as the criticism goes, it represents 'a single hemisphere of a single brain belonging to a 60 year old French woman' in the original Talairach paper atlas. The team at the MNI set out to construct an 'average' brain, based on many subjects, so that the target brain would be more representative of the normal brain. In forming the consortium, the scope of the average anatomical atlas grew even larger than the basis developed by Evans, and the MNI brain, based on MRI scans of 'normal subjects', was expanded from a few dozens (1989) to 305, with a goal of 450 (150 from each site) to be achieved by the end of 1998.

'These Normals'

The intermediate version of the average brain\textsuperscript{153}, the '305 version' was composed of young right-handed normals, 239 males and 66 females, mean age 23.4 (Mazziotta et al., 1997). In this atlas, the data were derived from a sample of normal brains, which are the brains of normal subjects. The normality of these subjects is based on what could be called a negative definition of normality—that is to say, subjects are normal if they are untraumatized, unmedicated, unaddicted, non-diabetic, not pregnant, not having had neuro-surgery, psychiatric or neurological disorders.\textsuperscript{154} Once selected, demographic, historical, clinical, neuro-psychological and imaging data as well as DNA samples were obtained for each subject (ICBM, 1997). These subjects were then scanned with MRI and these scans were averaged in Talairach space, thereby constituting the new target brain. Some of the arguments for a new atlas pointed to the original context, namely functional imaging. For example, the Talairach was said to lack representativity because the subjects of PET/functional imaging studies were usually normal young adults, while the Talairach atlas is based on the brain of an older woman (Mazziotta et al., 1997). Furthermore, the atlases could also be improved by being based on imaging, since atlases arising from invasive techniques, like intra-operative stimulation could not be relied on to provide data about the intact brain. Furthermore, these techniques are only used on subjects that have cerebral abnormalities, so that data from these sources can only be compared with, but should not be considered typical of normal brain structure and function (Mazziotta et al., 1997). Rendering normality in these atlases of the late eighties was a question of better, more representative brains, in order to better analyse functional data (from PET).

But other criteria for selecting an adequate sample for the new atlas are also linked to the HBP. The Report leading up to the Human Brain Project had recommended gathering baseline information about subjects in a standard way: age, handedness\textsuperscript{155}, sex,

\textsuperscript{153}This atlas is alternately described as being composed of 302, 305 or 450 brains. 450 is the expected goal, the other two numbers appear seemingly randomly. This probably reflects the data management issues that arise when trying to discipline data for integration, and the difficulty in working with a system that gets updated all the time, while trying to use it as a reference to write up a paper, etc.

\textsuperscript{154}This kind of sample called 'supernormal', because it eliminates so many of the features found in a 'normal' population.

\textsuperscript{155}Handedness as a criteria for analysis is closely related to notions that have been central to neuroscientific work (See Harrington, 1987): handedness participates in the logic of the two principles of organization of the nervous system: hemispheric specialization and the link between hemispheres and the contra-lateral side.
education level, or any characteristic features of the subject of group (Pechura and Martin, 1991). The Project announcement of the HBP also listed as an objective the constitution of an atlas in which subjects would be matched for handedness, age, and gender, and further introduced the notion that atlases should represent a population. The average brain atlas thus came to represent a population marked for a series of traits. Although the criteria of normality appear banal, these mutually constitutive features of sample selection and sampling bear further examination. Three new elements are introduced in the atlas through this process of selection: the notion of standardisation, of representing a population and the possibilities for retrieving sub-populations.

The procedures for dealing with subjects embodied the goals to standardisation and uniformity of the HBP. A program called NeuroCog was developed as an ‘automated subject interview interface’ (ICBM, 1997). All subjects were therefore ‘entered’ into the database in a standardised and automated way, for the purpose of reducing human error and making the process uniform. On the other hand, a kind of ‘randomisation’ was expected to occur, as the different centres selected from their local environment. Appealing to the first phase of the HBP, the researchers claimed that it would not aim to characterise an entire population, but to demonstrate the feasibility of doing so. But eventually, the data will “be representative of the population with regard to gender and race and will specifically examine the effects of handedness and gender on structural and functional brain variance (ICBM, 1997).” Clearly, the notion of a population-based atlas evokes population-wide applicability and relevance of such projects.

Furthermore, the list of attributes with which each component of the sample is marked takes on a particular significance in relation to the digital format of the atlas. In this respect, these atlases are more open-ended and less rigid than paper atlases, since sub-populations can be extracted, based on age, gender, race, behavioural abilities, handedness, or other features for which the data have been marked (Mazziotta et al, 1997). Up to now, age has been the most determinant feature, because of the research practices of recruiting young volunteers, and because of the clinical conditions investigated in relation to the atlas. Young brains were selected in the first instance, partly to provide age-matched controls for the activations studies, which often use university students as subjects. The age range for the first phase was from 18 to 40, and this will be extended to 90, as the Consortium focuses on studies of diseases of old age, “because [the
age range] conforms with the normal control population recommendations for the study of Alzheimer's and degenerative diseases of the brain (ICBM, 1997). This will also allow the comparison of data across seven decades and determine variance as a function of age (ICBM, 1997). Each feature for which the sample is marked can therefore be related to the data contained in the atlas, depending on the perceived relevance of these features to current research agendas. These features are made into differences which (could) make a difference in understanding the brain.

Automation and standardisation were significant to the handling of the subject interface and these processes were also important improvements to the objectivity of data handling. While the ‘slices’ in the Talairach atlas varied in thickness, scans were made with a greater regularity, according to standardised protocols. Digitalized brain scans could be handled (quantitatively) by computers, algorithms to transform brains of different shapes and sizes could also be multiplied beyond what was possible for ‘manual’ operations. Furthermore, the decision to develop an automated way to average scans across a group representing a population is also telling of this group’s alignment to the larger goals of the HBP described above. For example, a comparable atlas, also meant to improve the reference ‘target brain’, has used a very homogeneous sample (super-normal, right-handed Scandinavian males). Rather than averaging scans on a pixel by pixel basis, this group has chosen a set of anatomical landmarks to match brains to each other. An operator must identify these anatomical landmarks manually and visually, so that comparisons between brains in this atlas are based on homology (of significant anatomical areas) rather than quantitative averages of pixels (which are meaningless, other than representing a quantity, (a light or dark spot in a scan). For groups participating in the HBP, full automation and freedom from requirement for embodied expertise were priorities.

Besides the possibility of creating new average brains from sub-populations, this MNI atlas resulted in new ways of seeing the brain. The development of a new atlas showing variability had been raised by the Committee’s task force. While variability between individuals was known to exist, it was generally acknowledged to be ‘unknown’, in the sense of not measured precisely. Interest in variability seems to have grown in importance since the seventies with the development of CT scanning and post-mortem

---

158 Criteria for selection are generally similar in the other atlases, so that I will not discuss them at length again, but will rather point out where they differ in discussions of the other cases.
159 Eliminating the embodied user may on occasion be a displacement rather than a disappearance: instead of a trained anatomist, the use, or at least installation, of these programs might require an embodied software expert.
160 Nature published a call to action on human neuro-anatomy written by Francis Crick and Edward Jones in January of 1993, bemoaning the backwardness of anatomical maps in humans. The brain of the macaque is better known, the authors explained, because the methods used to discover the anatomy and connections of the brain cannot be used in humans, since they involve slicing brains and opening skulls. In remediying this lack of knowledge, however, the distinction between population and individual must be made (Crick and Jones, 1993). They suggest that a first step to solving this backwardness would be to construct average cortical maps.
co-relations of hemispheric functional differentiation (Galaburda, 1978). Variability is further constituted in these atlases, and with a special emphasis on the cortex. It becomes visible in the averaged brain. (See Figure 21.) "True" variability in the structure of the organ itself is preserved, while anatomical differences considered irrelevant are eliminated. Differences that don’t matter, such as size, are factored out by handling the digitised scans so that they conform to the same space. The average brain therefore focuses attention on the cortex as the seat of variability between brains. When the pixels in the scans are averaged, areas of greater variability are blurred, while in areas of lesser variability, the image is sharper than it would be in an individual scan.

![Figure 21 Galton's pictorial statistics: composite photograph of the military officer](Image)

Reproduced by permission from Seltzer (1992).

Note how the idiosyncratic is removed (an argument also made in the averaging of brain activation scans, see chapter 3) in favour of the common stable features, which are to be the larger, "gross features of the head". While this praise was also heard for the average

---

161 I suspect that this interest was always greater in surgical contexts, but was dealt with as a matter of expertise and clinical judgement, rather than requiring quantification. There seems to have been a regain of interest in anatomical differences between individuals as more attention was also paid to anatomical differentiation in the brain in general. For example, in the seventies when functional asymmetries were investigated, there were speculations that these would also be significant when observed between individuals: "Since there are great individual difference in the extent of asymmetries, it will be important to investigate whether these correlate with individual differences in functions (Galaburda, 1978)." I briefly return to this issue in the conclusion of this chapter.
atlas, the brain mappers' interest in the cortex, and the evolutionary value given to variability led to a further search for these variations. 162

The average brain is therefore the simultaneous creation of a better reference space, and a visualisation of variability. As a reference tool it is more reliable because of its greater representativity, based on the norm:

"Landmarks are derived from inter-subject stability of structures, 163 rather than by simple assignment based on the anatomical features of a single brain" (Mazziotta et al, 1997).

The MNI average brain has been widely adopted as a template on which to locate activations by a number of imaging centres, and incorporated as the template in SPM96, a data analysis package, making it the reference brain of a majority of functional imaging studies. 164 The focus of the MNI average brain shifted from being a more representative tool, in the sense of being based on a large sample of 'young normals' to being important to understanding the brain as variable. The atlas became a representation that captured essential features of the brain. What had begun as a better technique for localisation of PET activity (a better target brain and better computer programs for comparing scans) became an exploration of the normal brain, and of its variability which could be apprehended by multiple comparisons of scans.

**One earth, many brains: shifting from average to probabilistic**

To produce a tool to allow referring to an average, and through which one can see variability was not the end point for the consortium. The average atlas was acknowledged as important, but limited to a qualitative rendering of variability. Around 1995, a new

---

162 Compare with this description by Galton of the principle of his 'pictorial statistics':

"Composite pictures are...much more than averages; they are rather the equivalents of those large statistical tables whose totals, divided by the number of cases and entered on the bottom line, are the averages. They are real generalizations, because they include the whole of the material under consideration. The blur of their outlines, which is never great in truly generic composites, except in unimportant details, measure the tendency of individuals to deviate form the central type." (Quoted in Sekula, 1986).

163 For neuroscientists, what this robustness means is still uncertain, but there are suggestions that the greater variability of some structures might be explained by their more recent appearance in the evolution of the human brain—the same argument being made about certain functions, i.e. language areas less localized because evolutionarily more recent. Some areas are known to be more variable than others: i.e. hemispheric variability, central sulcus, temporal and frontal lobes (Evans et al, 1992). Also, by subtracting one hemisphere from the other, certain features appeared that were consistent with earlier findings, from work on hemispherectomy patients. Most of the references in these articles address functional differences as observed by neurosurgeons, or else inter-hemispheric differences, highlighting the significance of having access to the brain for this research.

164 Here too, numbers vary, ranging from 35 centres (Mazziotta et al 1997) to 100 in ICBM's Proposal (1997).
metaphor was appearing in print to explain the complexity and necessity of understanding variability in a probabilistic way. Members of the consortium compared the problem of cerebral cartography with that of terrestrial cartography: there is only one earth, one physical reality, but many brains, so that the cerebral reality needs to be based on a large sample, and reported probabilistically. For example, the average brain described above is praised because it provides indications of the common features of the brain within a population.

**AverageBrains and Probable Labels**

Another type of atlas was developed by the ICBM as researchers addressed variability in increasingly complex ways, aiming to quantify it, and improve on what was perceived as too qualitative a demonstration of variability. This move to recover variability led to new applications for atlases and digital tools. In the course of developing the average atlas, a very specific type of expertise developed concerning the possibility of manipulating ‘voxels’ in scans. In the average brain, these were ‘registered’, disciplined into a standard space, and their value averaged—that is to say that their value, corresponding to a degree of darkness or brightness on a grey scale, was averaged. Further work at the MNI enabled the group to label voxels in scans for other types of features, namely to label the type of tissue represented or an anatomical region. The scans of one hundred brains were labelled by a trained operator (usually a neuro-anatomist) who ‘painted’ brains, with a pixel-wide ‘paintbrush’, identifying and labelling each area.

Another layer was therefore constructed around the scans, relating voxel and label. This relation was rendered not only quantitatively, but also as a probability:

“a probability map is then constructed for each segmented structure, by determining the proportion of subjects assigned a given anatomic label at each voxel position in the stereotaxic [reference] space. (ICB webpage).”

This kind of atlas indicates that (based on the sample of brain scans processed), at location $x,y,z$, there is a 56% probability of finding structure A, a 13% probability of finding structure B, etc. This means that locations in a scanned brain, placed in Talairach space, could be known as having a probability of belonging to a certain anatomical structure. When reporting activations from functional imaging studies, the

---

165 This can be found in Ward (1996), Mazziotta et al (1997), Frackowiak et al (1997) Toga and Mazziotta (1996). See also framed text, in chapter 3. Another aspect of the perceived greater complexity of the brain was also formulated by contrasting terrestrial and cerebral cartography: structures in the depth of the brain (cortical folds) must also be represented, hence showing surfaces is problematic, since they do not reveal these, leading to recommendations for 3D representations (Swanson, 1995).

166 A computerized list of neuro-anatomical terms called BRAIN TREE is under development at the MNI, which will serve to relate various nomenclatures in use in the neurosciences to the atlas’ co-ordinates ($x,y,z$ = __ or __ or __)
anatomical area corresponding to the functional area can therefore be described with
degrees of certainty.

In these atlases, the brain represented relates to group data, as in the average atlas,
but besides putting brains into a common space, the relation between them is labelled and
rendered as a distribution. It is also an atlas whose objectivity can be constantly
transformed. As each scan is added to the set, the probabilities of the atlas change, so that
the statistics improve as more information is added to the set (Mazziotta et al, 1997).
Quality therefore improves with quantity in this framework. Canguilhem’s aphorism, the
norm points to the rule and extends it, pronounced some 50 years ago, seems
extraordinarily appropriate to the conceptual underpinnings of the Probabilistic Atlas. In
practice, because the anatomical atlas serves as a basis for other work, on the localisation
of functions, for example, the atlases are ‘quarantined’ and periodically updated, a
process which does not always go smoothly, as I observed in the field.

While human intervention (usually that of a neuro-anatomist) and its dreaded
inconsistencies were involved in labelling for some of these atlases, others were fully
automated. The need to standardise labelling between observers and remove the observer
is a clear aim of the Consortium, the attainment of which they consider to be hindered by
the difficulties posed by the variability of the brain. This work also extends the
technologically mediated understanding of variability of the brain (apprehended in the
average brain described above) to other aspects of neuro-anatomy. Furthermore, rather
than visualising variability, as a more or less blurry area on a representation of averaged
scans, this approach provides a quantitative understanding of variability for a population.
Anatomy, in the paper atlases, was the correspondence of a label to a structure, a relation
of identity. Structures are here defined according to their “occurrence” in a data set. Like
the average brain, this too is a new representation, clearly different from traditional
understandings of neuro-anatomy. Whereas in the classic anatomic atlases the goal is to
identify the structure to which a location in the brain of a given individual brain belongs
as unequivocally as possible, here, locations in the brain are defined as to their identity, in
terms of a representation that stand for a population. When recast in terms of a
population, across large numbers of scans and in probabilistic terms, relationships
between label and structure are relative to a sample, the identity of a structure becomes a
question of probability. The particular uncertainty that had entered these atlases with the
goal of encompassing variability is therefore resolved by being given a quantitative
evaluation.

Pathological Probabilistic Atlases

A similar recasting of notions of pathology also occurs in the probabilistic atlases
of disease. Between the early and mid nineties, the MNI developed expertise in the
analysis of large numbers of scans as the Consortium work progressed, linking various
kinds of software into ‘analysis pipelines’. Using these techniques, the MNI has
embarked on a commercial venture in partnership with a company that produces scanners,
and formed a company (Neurovision) that runs the image analysis component of clinical drug trials.

In this work, voxels are labelled for the type of tissue they represent (grey matter, white matter, CSF or lesioned tissue), instead of being 'painted' according to anatomical labels. This means that the volume occupied by different types of tissue can be automatically calculated across large samples, and in scans taken at different times. Based on the measurement of statistically significant increases or decreases in volumes, these tools have been applied to clinical trials, producing quantitative data about the potential decrease of a 'lesion' load, in relation to the administration of a placebo or drug.

Through one contract, the centre compiled 1850 scans of 460 people with multiple sclerosis, which have been entered into the MNI reference space. While the company is interested in the effects of the drug under trial, ("the numbers"), the imaging data has remained at the disposal of the MNI. For its own research purposes, the MNI has used the data from these clinical trials to generate the MS brain, a 3D representation which indicates the likelihood of the location of lesions in MS. As a result of new modes of data-handling, aggregated scans come to show not the brain of a patient suffering from MS. Rather they show the image of MS itself, across scans, across patients, across the clinical manifestations of symptoms: it "shows the most likely locations for MS lesions within a population and is a convenient way to distil a large amount of population data into a single entity (ICBM, 1997)." This view of disease as concentrated in a single representation has also been used to describe other atlases, such as this one built using scans of schizophrenic and normal subjects:

"a concise numeric and visual summary of the group as a whole" and the statistically analysed difference between the two is an "image [that] presents a descriptive picture of the size of group differences (Andreasen et al, 1994)."

Here, the essence of disease arises from the automated, large-scale comparisons of standardised scans. The atlas shows the 'ideal', as defined by Daston and Galison. But this ideal, rather than being based on the observers' mental distillation and expertise, is the result of a pipeline analysis and a framework for comparing brain scans.

In terms of traditional atlases, this points to an important shift from the tendency to show the 'characteristic' representation of a diseased organ, a convention that is especially long-standing in anatomy (Daston and Galison, 1992). Here however,

---

367 MRI detects a signal at the molecular level, and these signals can be made to contrast between different types of substance that make up the brain and head.
368 The MNI space encompasses only the brain, thereby ignoring lesions in the spinal chord. This is but one unintended consequence of brain mapping's focus on the cortex.
369 As anatomy shifted from a description of structures to an anatomy based on interpretation of symptoms and their relation to anatomical lesions (Davis, 1981), medical atlases came to represent these new relations in 'characteristic' representations so that they might be learned and recognized by medical practitioners.
pathology is constituted as the distribution of lesions as identified through automatic processing.

**Pipeline Dreams**

In pursuing this work, the lab was also faced with more complex issues of standardisation and the mutability of mobiles. The expertise to handle hundreds of scans automatically and to analyse them quantitatively depends on the coordination of scanning from the imaging sites of these trials. The coordination of work done at these sites required the involvement of a trial manager. Some of the stories he told about ‘being able to rely on some centres’ or knowing which people he could call on when in a crunch and pressed by time, often involved notions of trust, the need to visit sites to get to know people, the need for a certain embodied kind of work. Maintaining the system that led to the production of the atlas required human judgement (like that of the anatomical illustrator?), though displaced to a different point in the production of representations. Insofar as all scans must conform to pre-determined parameters in order for the software to operate, this dependence on standardised procedures is a condition for the use of data in these new atlases. ‘Mobiles’, especially digital ones, are not so much immutable, as recreated according to conventions, and allowed to circulate in the locales where these conventions are operating.

Further applications for the probabilistic atlas were also being developed during one of my visits to a lab and give insight into the importance of avoiding observer intervention, for the construction of the automated processing of average brains. Analysis software to identify some of the sulci (‘valleys’ in the cortex) from MRI scans was being developed and validated. The software currently identifies the probability that a fold corresponds to a given structure, the central sulcus for example, but the goal is to ideally be able to identify (on a given subject’s scan) the desired structure. Like in the other atlases, the algorithms are validated manually, a tedious and time-consuming job, requiring not only neuro-anatomical training, but also the ability to learn to see with the display programs which handle these images. There could be some difficulties with ‘visualising’ (in the mind’s eye) a three dimensional structure from the three flat slices provided by the computer (for which incidentally the computer was said to be more powerful since it could run tests on forms), or going from book knowledge to 3-D representation.

But while tedious, this work is done with the understanding that manual validation will confirm the results of the automated tool, and liberate future users from the need to ‘paint’ the structures manually, and ensure the mechanical objectivity of the process. While human intervention may be needed in practice, the ideals pursued are automation and standardisation. The students and researchers working on these tools often reported avoiding human inconsistency, or removing the noise of human error as a self-evident
motivation for the work. This perceived need to avoid human fallibility was also visible in the instructions and support work provided by the local computer experts to researchers: programming was done with the goal of avoiding 'interaction', and automating data processing as much as possible.\(^{170}\) The use of these automated tools therefore relies on the normalisation of the process of analysis (assumed after validation) and the 'normality' of scanning procedures and of the brains under scrutiny. The ideals to which these tools strive consist in removing the individual, both as idiosyncratically ill (MS is defined across a population) and as subjectively (inconsistently) interpreting or manipulating data. This approach is productive of frameworks and models, purified data, undergoing disciplined transformations in order to yield an idealised object.

**Variability (Diagnostic) Atlases**

Beside the average and labelled probabilistic approach, another type of atlas has been developed by the Consortium. The norms that are established by the representations discussed up to now are built around two concepts: that of the average as a reference for a group, and the possibility of illustrating or determining statistical probabilities for features of a group. But the projects of the Consortium are more ambitious than simply providing better reference tool for the field, and as mentioned above, focus on building a normative model of the human brain with clinical applications.\(^{171}\) Building on the probabilistic labelling of anatomy in the ICBM project, one of the goals for the application of probabilistic atlases is to serve as a diagnostic tool:

"Such capabilities [of giving probabilities for features] allow for a rigorous analysis of normal variability, as well as variability in structure and/or function as it relates to disease, such as those thought to be associated with mental disorders and other brain pathology (Huerta and Koslow, 1996.)"

\(^{170}\) Alongside this approach to objectivity through automation, I also observed a number of (local?) strategies for using or checking on the automated process. Some types of scans were expected to be processed unsuccessfully, because they had been made according to non-conform scanning procedures (for example, they are clinical and not research scans) and some types of brains were expected to fail (because of pathology). Users of automated software would call up images from different stages of analysis, to run little tests to check what had been changed in the image data. In cases where the reasons for failures could be typified, attempts to deal with it structurally were made.

\(^{171}\) The determination of common standards of normality involves agreeing on a measurement space, as amply discussed above. Another aspect of this process is the calibration of instruments used in measurement. While this aspect will not be discussed here for the sake of clarity and brevity, the calibration of instruments through the use of 'phantoms' (either real, standard objects, or else data-sets to be processed) which enable different centres to evaluate the performance of their instrumentation is part of the work pursued under HBP grants, and also has some roots in the work of neuroimagers in the eighties. See Mazziotta (1987), Rapoport (1991). See also O'Connell (1993) for a discussion in a context of bodily measurements/biometrics, and Knorr-Cetina (1999) and Traweeck (1988) for further discussions of calibration in another physics instrumentation context.

153
To understand the logic of this atlas, it is useful to think again of the single voxel being manipulated. In this atlas, the measurements made around this voxel concern its relation in space to other voxels. Specifically, this means that the direction and distance a pixel has to be 'moved' to be aligned with a given position is measured. This provides a variability map that shows by how much a given voxel can vary.

DEFORMABLE PROBABILISTIC ATLAS

So whereas the average scans showed the essence of variation between the anatomy of brains, in this kind of atlas, variability is to be understood statistically, as a feature of the brain that can indicate normality or pathology. In order to evaluate a particular case, the reference space must still provide a measurement space: "...any comparison of individual against normative data must still account for anatomical variability among individuals, particularly in cortical folding (ICBM, 1997, 211)." The differences between the subject’s scans and the atlas is then to be quantified and determined to be inside or outside the normal range.

The proposed probabilistic atlases will relate a new subject’s MRI to each and every brain in the archive by warping the new brain to the archived ones. The structures are then compared as to their distribution, and a probability is issued, to determine the likelihood that the new subject’s data falls within the configuration of the archived brains. Two types of representations can be made from this atlas, either 'variability maps', based
on a group or population, and ‘probability maps’, indicating the relationship of one individual to this group.

The particular manipulations of the voxel here involve, like in the preceding atlas, being brought into a standard space and labelled as belonging to a particular structure. A further layer is added in these atlases: for a given group, the distribution of voxels in space for a structure is further calculated. This provides a variability map, in which the normal range of distribution for a brain structure is given as a coloured representation, with ‘hotter’ colours representing greater variability. In keeping with the concept of variability developed from the previous atlases, some areas like the cortex have a greater range (hot colours) than areas that are more stable across subjects (cool colours). A second type of map is produced, by comparing a subject’s scan to the probability map. The individual’s scan is therefore coloured according to whether voxels fall within the normal range (cool colours) or else represent a deviation from this range and possibly represent a pathological variation (hot colours).

Figure 23 Probability and Variability Maps

These images are hard to reproduce and best seen as a three-D representation on a colour monitor, but basically, you can see an image of a patient’s brain compared to a population in terms of variability of the brain. Where a voxel falls outside the normal probability for that part of the brain, it would appear in red. The goal is to be able to associate patterns of abnormal variation in specific patients, with particular conditions (Alzheimer’s, schizophrenia, etc).

Reproduced from http://www.loni.ucla.edu/~thompson/MedIA_pics.html
Courtesy of Paul Thompson, UCLA Dept of Neurology

155
The individual scan is only meaningful in terms of the database, once it has been ‘overlaid’ with the significance that comparison to the norms imparts to it. Normality emerges from large scale, quantitative comparisons, and analysis based on voxel to voxel comparisons can provide a picture of a disease where no typical pattern was visible:

“...In the future, precise models for the cortex that encode information on structural variability will provide a better understanding of the complex regional changes that occur as a result of developmental processes or under pathological conditions. Accurate quantitative measurements may then be used to obtain objective criteria for conditions such as global or regional cerebral atrophy and for the assessment of subtle gyral or sulcal anomalies that may be specific to certain disease states. (Thompson et al. 1997).”

This atlas can handle scans in their typical, clinical form (as images) since it is built using pattern recognition principles. This feature might significantly further the clinical application of the atlas. A level of ‘cognitive familiarity’ has been shown to play a role in circulation of classifications and knowledge claims (Hiddinga, 1995; Galison, 1997). By producing results in form clinicians already use it, scanning databases are expected to be more acceptable to these users.

Based on ideals of large-scale automated data-gathering and data analysis, these anatomical atlases, be they average, probabilistic or deformation-based, have provided new tools for manipulating and comparing brain scans. They have also been the context for the production of new objects of scientific knowledge: the average normal and ‘sick’ brain, probabilistic anatomy, the variable brain. Finally, and directly in relation to the HBP, atlases have provided idealised brains as frameworks for integrating data across technologies and populations. The goals of the researchers for integrating other levels of data are parallel to those developed around anatomical data. The ICBM plans to pursue a probabilistic approach to the brain for other levels of brain anatomy and function. Plans for the next five years of funding involve establishing two more probabilistic levels. Cytoarchitectonic data will be gathered, and the variability of the brain’s anatomy will be defined on the level of distribution of biochemicals (and receptors at cell level) which have a functional component, and therefore serve to link gross anatomy to the level of function. The functional level will be based on PET and EEG studies of function (ICBM, 1997).
Figure 24 The Potential of the Integrating Atlas as Proposed by ICBM in 1997.

Note the conceptual and technical work that separates this representation of 'integration' from the integration of levels proposed in 1992 (Figure 20, page 140). The representation of knowledge has been streamlined: each subdiscipline is a version of the 'same' brain. The relation of these various levels has become defined as one of standardisation of formats and of translatability.

Reproduced by permission from Neuroinformatics (1997).

In terms of the larger goals of the HBP, the average brain has therefore become a reference space, which can be used to integrate other types of data, besides MRI or PET scans. Resistance to integration—The UCLA component of the consortium has gathered digital images of post-mortem tissue (which provide better resolution than MRI), that will be matched to the reference space. In principle, other types of data can be integrated as well, adding a functional level and elaborating functional landmarks. The consortium describes the integration of this data as likely to lead to an understanding of the correlation of function and anatomy, one of the general goals of the Human Brain Project.

"We make no assumptions about the relationship between structure and functions in the human brain, at either a macro- or microscopic level, except to state the obvious, that these relationships are complex and poorly understood. Further, we are not proposing that we will unravel this complexity with the data collected in the context of the consortium program. The development of a probabilistic reference system and atlas for the human brain simply provides the framework in which to place these ever-accumulating data sets in a fashion that allows them to
be related to one another and that begins to provide insights into the relationship between micro- and macroscopic structure and function (ICBM, 1997)."

In spite of the modest posturing of the proposal, the production of landmarks as the bases for comparisons is not entirely theory-free, as discussed in this chapter, and relies first of all on the assumption that anatomical landmarks are not the only determinant of brain architecture. A set of tasks will be developed, chosen to reliably evoke functional landmarks across subjects and modalities (ICBM, 1997). The project of establishing ‘robust’ activation that will be found across subjects in a population, and entering them in a framework where they are directly comparable to other levels of data, relies on the possibility of equating levels of brain organisation, which is not a trivial assumption. Again, the space of the atlas is key to integration: once the data occupy a similar space, the relationships between these levels can be explored.

What began as a repository of anatomical data, a brain more representative because based on multiple subjects, has become a framework for integrating many levels of data and articulating relationships between them. The reference tool becomes site of discovery, as new knowledge emerges from compilations and comparisons, as scans become more easily available, and methods for compiling and comparing them automatically are developed.

New Norms, New Normality

Totalising Atlases

At the beginning of this chapter, I evoked two key issues from discussions in the Decade of the Brain: the brain as a set of voxels known in n-dimensions, and the crisis of information in neuroscience. Both issues are part of new modes of data acquisition and handling, as described in this chapter through comparisons of ‘the normal’ in various forms. To return to the rhetoric of the Decade of the Brain: What will save neuroscience? (Bower, 1996) The answer in a single neologism: neuroinformatics. But it should also be clear after discussing the new atlases that in being saved, neuroscience and its definitions of normality will also be born again.

By comparing Figure 20, on page 140, with Figure 24, one gets a sense of the conceptual and technical work that has taken place in the course of the HBP. Figure 23 shows simple dotted lines between various types of data, various versions of the brain that have been part of very different research traditions, embedded in different technologies and methods. This chapter has meant to show the work need to establish a framework for integration (a normal brain) and objective processes of translation and manipulations (algorithms, collaborations, pipelines, groups of subjects). The brain is then normal in relation to these many standardised and black-boxed processes, and marked in terms of a

1, 2 Jerome Engel and John Mazziotta (1984) had speculated that there might be such a set of tasks that could be used to evoke particular function and highlight dysfunctions in epileptic patients.
number of features with potential explanatory powers (sex, age handedness, etc.). Living and dead brains are also to be correlated in this atlas; the effects of death erased by a proper algorithmic correction.

The resources described in this chapter all have in common the use of large-scale sampling and analysis, and the redefinition of representations of the normal brain. These common features point to the intersection of two important themes in the constitution of atlases as digital resources. First, they speak to the ‘needs’ of neuroscience to develop ways of pooling data, and second they articulate the relation of both the advancement of knowledge about the brain and of the normal to the pathological as being apprehensible only through this pooling. The means selected and developed to achieve this pooling in the HBP resources have focused on the use of digital and electronic media. Through the constitution of large amounts of digitalized data, criticism of the earlier atlases, which used only a few specimens or composites, were answered. Typical or ideal representations are not suitable for these atlases, where quantity seems to hold the answer: atlases therefore have “an open data structure for any future enlargement of the sample size (Roland and Zilles, 1994).”

The gathering of large samples, however, is made possible by the development of conventions, standardisation of formats and automated procedures. Scans gather added value, by virtue of their being mobilised in a Latourian sense, while quantification, analysis and evaluation of data, accomplished automatically, guarantee their integrity as data. These features point to the constitutions of objectivity in these atlases as a rejection of the subjective observer, and reliance on the regularities in nature that can be discovered through statistical analysis. While earlier atlases are highly observer-dependent, use purely qualitative measures, are based on “pure visual inspection”, they also do not allow generalisations, due to the large variations in extent and topology between individuals (ICBM, 1997). Complex representational strategies either distil individual features to form average brains and make these into a higher truth, warranted by the stabilities across the multiple instances they represent, or else embrace these differences and render them as exquisitely as possible for each individual. Furthermore, the automation towards which the Consortium strives in all aspects of the atlas (pipelines, etc.) is also welcomed as an improvement over qualitative, human intervention and the subjective choice of landmarks for matching data about different brains or from different modalities. The possibility of quantifying the experimental error, as opposed to relying on qualitative assessments of variation based on visual information of a single observer (Mazziotta et al, 1997), is also stressed as an advantage of these new atlases.

These new digital resources also involve a shift in the way expertise is to be applied to the use of atlases. Consider this new definition of the success of an atlas:

"The success of any brain atlas depends on how well the anatomy of individual subjects match the representation of anatomy in the atlas (Toga and Thompson, 1998)."
Here, the comparison between an atlas and a new case to be evaluated is based on matching, on the possibility of warping one brain to another automatically and evaluating this match with a degree of certainty or a quantitative evaluation of 'fit'. Whereas the traditional atlas is heuristic, and the observer (surgeon or anatomist) must make a judgement call in applying her knowledge, in the new digital atlases, a degree of uncertainty of a location is assigned to the identity of a given location (a voxel, in practice), and expressed explicitly as a probability, a degree of confidence.

Part of the reason for this shift might be the reconfiguration in the digital context of the subject/object relation, which Daston and Galison posit as the defining axis for understanding objectivity. The automated evaluation, what I have termed database diagnosis, might indicate the extent to which the pole of the 'subject' has been diminished in this context. The observer hardly appears at all in digitalized work based on a virtual objects such as the normal brain of these atlases, and then only to test the pipelines, not the accuracy of the transformations—for which there are other automated testing methods. The subjective mode of the earlier atlases, described in recent tests as purely qualitative, purely visual, is also purely dismissible, in light of the HBP's antithetical purity of standards and automation.

In the atlases discussed above, the digital form of scans plays an important role. Other attempts have been made to archive and use images (especially photographs) for scientific purposes, to go from the idiosyncrasy of the individual representation to the elucidation of the 'type' through multiple comparisons, involving a merger of optics and statistics (Sekula, 1986). The images produced by Galton are perhaps best known, but form only one of several projects of archival control of, and through, photography in the fields of medicine and law (Tagg, 1980a,b; Sekula, 1986). But the strategies for managing evidence developed in some of these projects are also manifest in these atlases of the brain.

In order to deal with large amounts of data, Galton chose to collapse the archive into the photograph and capture the 'type', while Bertillon incorporated the photograph in the archive, to capture the individual. This tension between the revelation of phenomena across instances and the identification of a particular (deviant) instance from large amounts of data is also found in these atlases. In the multiple sclerosis and schizophrenia atlas, the disease is invisible in a single case but apprehensible across many scans. With variability maps, the focus is rather on identifying the individual, in relation to the archived data. The individual can be overcome, so that the essence of disease arises, or that very individuality can be sought out.

---

171 The photographic archive arises in conjunction with the emerging social science of criminology and the professionalisation of police work (Sekula, 1986). New systems co-emergent with brain archives are introduced in chapter 3 and discussed in chapter 6.

173 This is literally so: Bertillon's system was developed for the application of anthropometry to police work, namely the catching of criminals.

175 I return to this specific point in chapter 6.
But, again, digitalisation differentiates these particular atlases. If the classification of photographs was frustrated by the “messy contingency” and the sheer quantity of available photographs (Sekula, 1986), in the case of scans, digitality holds the promise of tighter control over data, because the content is considered thoroughly quantifiable. Differences between scans that would not be evident to the naked eye of the observer become apprehensible through a quantitative analysis. Quantification, in turn, forms the vehicle for a more efficient circulation of knowledge claims (Hiddinga, 1995). The objectivity of the brain atlases does not reside in its imagistic effect, but in the bits of numerical data it contains. As digital tools, these atlases have “no print-on-paper” equivalent, and seem to be introducing a new digital mode of objectivity.

Resistance to Integration

The power/knowledge relation proposed by Foucault and elaborated in science studies by Latour, Rouse and others is especially relevant to discussions of large repositories of information, and their potential for reconfiguring social categories. Centres for calculation in which representations are cascaded (Latour, 1990) are important for the constitution of scientific dominion on spheres of life. The argument can be posed as follows: when such deployments are based on gathered measurements, the greater the investment in the form, the more solid the object (Desrosieres, 1993). The concentration of knowledge, however, is not the apex of a pyramid, since if power is to be exercised, the link must be made ‘back’ to the many constituting loci. Norms which are derived but not applied are not powerful. There are many ways in which such deployments may fail, just as there may be obstacles to standardisation.

While the build up of the maps and atlases into databases would be presented as seamless by the developers of these resources, the move from tool to model is not always perceived as so continuous in the larger neuroscience community. The electronic and digital resources are acceptable to most, if they are used as tools.

“BrainMap, ...could be useful for younger people who are writing papers and don’t know the literature, and may well be useful for those who think they know it but don’t.”(Senior Researcher, trained as psychiatrist)

“the level at which we take that sort of integration seriously is at an operational level, what we need, need for the future. For example, MNI templates are being used here because that template is likely to become the standard. So we are planning for integration insofar as the SPM maps will be comparable with the probabilistic atlas (Senior Researcher, trained as psychiatrist). “

\[^{176}\text{The downfall of these efforts to develop systems of photographic documentation and administration was caused by the cumbersome nature of the processing of suspects, the rise of fingerprinting as an easier system, and more generally, the demise of an optical model of empiricism, according to Sekula.}\]

\[^{177}\text{A term coined to characterize WWW advances (Atkins, 1996).}\]
But there is some resistance to the ‘theory of science’ component, and the promise that they will yield new insights if they are developed. Such objections are sometimes formulated as critiques against the HBP as Big Science, or as protests against the assumptions that new knowledge arises from gathering data.

“Scientific integration is usually spared by what you need to know and if you’re good at your job you’ll go and find it, and prescribing integration (personally I think is) it’s probably a waste of time, and it’s usually promoted by people who have become dissatisfied or are having difficulties finding the resources to do the science. I haven’t found it useful databasing, or meetings that try to put together people from different fields, to see what would and I’ve never see anything concrete coming out of it. When people have defined a clear problem, and need to solve it, they go and find the people they need (Senior Researcher, trained as psychiatrist).”

The pipeline and automation logic of these atlases is evocative of either second-rate modes of pursuing science, or of a bureaucratic and managerial style of science that is not driven by ‘the questions’.

Besides these principled objections to this form of neuroinformatics, another kind of reservation about the project is also heard. While the integration of more data and more types of data increases the power of these atlases, the rigidity of these tools may increase proportionately. These atlases also reinforce the importance of certain features which I pointed out in the course of this discussion: variability, ‘populations’, demographic traits, etc. While provisions are made for ensuring the translatability of many types of data, including new dimensions along the way may not prove feasible, leading to either the abandonment of the database or reinforcing the elements that are included as those most important in understanding normality and disease.

As well, even those who embrace and contribute to the project of the ICBM sometimes resist the full application of the logic of a probabilistic database; the users of these atlases require a certain obduracy. While praised for having ‘open data structures’ and therefore continuously improving statistics, a system of ‘quarantine’ has been developed around the ICBM database, so that users might have a reasonably stable basis on which to perform analyses and write papers. This requires careful weighting of the potential benefits of improvements to the analysis software (the pipeline) and the need for robustness and stability of a research tool, in the course of pursuing a research project.

While it is perhaps trivial to state that the obstacles to a neuroinformatics version of

---

178 Other projects in the HBP have opted for an object-based structure, where links between units of knowledge are looser, conceptually closer to the traditional ‘encyclopedia’, with its entries on various kinds of topics, than the ‘atlas’, with its grids and cross referencing systems.

179 The structure of research may come to change to fit this type of tool but currently, the traditional data gathering, analysis and paper writing cycle lasting a few months does not accommodate frequent update of tools.
neuroscience are proportional to its ambitions, these few objections are surely a useful reminder of this point in the face of such a seductive project.

Collapsing Atlases, Growing Databases

I have been describing these resources as atlases. But labels do not come easily to these resources, and neuroscientists themselves, in turn celebrate or struggle against the collapse of labels that define traditional categories of reference works. A few examples:

"atlases are essentially databases which are represented as maps" (Toga and Mazziotta, 1996).

"Digitised maps are databases since they can be queried" (Toga and Mazziotta, 1996)

"the databases essentially become models of brain structure and function" (Roland and Zilles, 1994).

These definitions collapse, again, because of the digitality of the data that allow manipulations in order to merge formats and sources of data. This results in atlases that are powerful tools for integrating various kinds of data, because of the means for translating various kinds of neuroscientific data into the virtual probabilistic space of the brain. It is therefore in the context of the developments analysed in this chapter that the promise at the beginning of this chapter can be made by the principal investigator of ICBM. The brain will be known as a given composition of voxels, and information about each voxel will be available through databases, which can include an endless number of attributes of the brain, investigated by an equally endless number of techniques and sub-disciplines.

The new atlases also function as tools for discovery, for research purposes or for diagnostic applications. “Computerised brain atlases are not only for the identification of structures but are also becoming a research tool for parcelling the human brain functionally and structurally and for meta-analysis of brain function (Zilles and Roland, 1994).” The importance of notions like data-mining have been emphasised in more recent reports on the HBP (Sheperd et al, 1998). Along with the development of these virtual brains, the locus of neuroscience research can arguably be said to be changing, moving from wet labs to voxel space, from workbench to console and monitor. Similar moves in biology, especially in relation to the Human Genome Project, have been labelled a paradigm shifts, in biology (Fujimura and Fortun, 1996). While the efforts in neuroscience are pursued on a much smaller scale and later than those of the Genome community, there are signs that the atlasing mode of work is having an impact on some research efforts.
Perhaps most striking among these is the close, almost synthetic approach of atlassing practices and of those for running clinical trials. Pharmaceutical companies are especially interested in the 'pipeline' analyses the MNI can provide, since the companies can easily perform 'audits' of the results provided: automated manipulations are easily recorded and verified. The manner in which authoritative, trustworthy results are produced in ICBM and the standards to which pharmaceutical companies must answer are very compatible.

But such close collaboration is not restricted to projects which might be expected to have a more 'bureaucratic' set up. Bodies dedicated to the pursuit of scientific research, like the NIH, are also interested in the pipelines, as they seek to make use of large samples. In the "children's brains project", the NIH were worried about inter-rater agreement, and established a close collaboration with the MNI to pursue this research. During an interview, a leading researcher also expressed the following, when asked about the work of the Consortium:

"Oh, this is exciting. That is a really unique way to look at very subtle differences between individuals and brain anatomy. You wouldn't be able to do that with the naked eye, and you wouldn't be able to do it with ten subjects. You need a large database, you need sophisticated automatic ways to extract morphological features and then analyse them statistically in 3-d space, for all 100, 200 subjects, I think that's-I completely, well, we were talking about functional imaging—I see this as even more promising in a way, than functional imaging, to an extent (Senior researcher, trained as physiologist)."

The system being put in place for cascading data is even more powerful than the imaging technologies that enable gathering the data! At the MNI, such "extracted morphological features" from large databases have recently been linked to 'normal' brain development as measurable on scans, with the suggestion of using this approach in an evaluative, normative way. These results have been surrounded by speculation about the possibilities of developing 'testing' or even early screening for these signs of illness. These are only a few signs of the alignment of databasing, research, diagnostic and screening, but arguably indicative of the larger issues addressed in this chapter about changing notions of normality, transformations in the ways of investigating and evaluating it.

Perhaps most significantly for potential future clinical deployment of these atlases are the new ways of drawing boundaries between the normal and the pathological. Canguilhem pointed to the tension created by looking at the physiological in terms of frequency and the pathological in terms of rarity along a single distribution, with the result that there is no categorical difference between healthy and sick life (Canguilhem, 1978). These differences are being sought in brain scans. It has been suggested that with

---

180 Sekula analyses the relation between photography and the archive at the end of the nineteenth century. and finds that "the central artifact of this system is not the camera but the archive (Sekula, 1986). In both instances, faith is placed in the administration of visual difference rather than in the optical truth (in the sense of Daston and Galison, 1992) of the camera or scanner.
the rise of brain imaging, deviant brains will come to be judged on deviant looks, like in
the physiognomic systems of Lavater (Stafford, 1996). But while typologies and systems
of difference are also involved in this project, the armamentarium involved in these
projects is radically different. The traces measured are not hand drawn sketches of
profiles, interpreted by a human with a trained 'eye', but rather rely on complex
digitalized processes and technological rationality.

Boundaries of health and illness are matters of great cultural import, and the
efforts deployed to establish such boundaries are telling of the anxieties being quelled by
these projects. The conditions being investigated until now (multiple sclerosis,
Alzheimer's, and schizophrenia) are without clear aetiology, consist of a broad range of
symptomatic manifestations, are diagnosed based on complex clinical evaluations, and
are conditions for which therapeutic measures are limited. Complex statistical
manipulations in abstract spaces make these phenomena visible, and the hope of eliciting
a physical trace might partly warrant the investments required to make brains visible,
measurable and translatable into a virtual space. Database diagnosis may therefore be
complex and abstract, but it is better than no diagnosis at all. Again, this exercise is only
possible in a context where statistically enhanced digitality is accepted as a mode of
knowledge. From science policy goals to new forms diagnosis, neuroinformatics
redefines what is to be known about the brain, and how to go about finding it out.
The past chapters have analysed the development of a new set of representational practices in a new area of research, brain mapping, and its constitutive dynamics of digitalisation and biologisation. Insights have been gained into the way conventions for making representations change, and into how the circulation of representations plays a role in creating new objects of knowledge. Before returning to the theoretical issues addressed in the first chapter, regarding the study of scientific knowledge and practice in terms of representations, I wish to further draw out the implications of digitalisation and biologisation as analysed in the previous chapters.

From the demonstration of the progressive development of PET, from neurological scanner to brain mapping tool, and its association with other technologies, the old model of the ready-made technology, simply revealing nature, is once again shown to be incomplete, and even misleading. PET provides not so much a window on the brain, but gradually becomes part of a complex kaleidoscope of representations, which constitute brain mapping practice. It is through an examination of the novel and complex nature of this kaleidoscope that this analysis provides new insights. The shifts in representations sought and obtained with PET constitute a move away from an optical understanding and towards a digital mode of knowing. Key aspects of the development of a new technology, such as the establishment of a 'baseline', therefore become a different kind of work from that performed around the x-ray or the ultra-sound—both originally developed in optical contexts. Quantitation of the scans produced, mathematical transformations to insure the validity of a 'baseline', and quantitative evaluation of variation from this baseline all become intrinsic to the usability, objectivity and scientific standing of these new representations. Furthermore, automation of all these processes is highly valued ideal, and more often than not, an actual goal of any new representational practice in this context. Clearly, the importance of quantitation and automation in this shift have implications for what have been the dominant features of the use of representations in medical and scientific practice. Visual appearance, pictorial accuracy, observation and visual judgement all become not only obsolete, but downright suspect in a digital space. Transformation algorithms, averages, and statistically validated analyses replace what is fallible, variable and inconsistent in both subject and object, in both observers and the brains studied.

When coupled to biologisation, as it is in the case of brain mapping, digitalisation is not just a new approach to making technology and its inscriptions meaningful. The biologisation of mind in the past decade has had to rely on the production of digital representations to establish traces of mental activity in the brain. These two processes conjoined thus form a new approach to the normal and the pathological, to the determination of states of health and disease. Digital representations have served as the context into which mind (as differential blood flow) and brain (as anatomy) can be translated, coming to exist as two features of a voxel, the mind-in-the-brain on a screen.
The biology of mind has therefore also been re-formulated in terms that make it amenable to being represented as a feature of a map, a physical difference in relation to the digital space of the brain. This translation to the digital does not leave the biological unchanged: what counts as anatomy, for example, is transformed, just as this integration loads the digital with the possibility of constituting a meaningful representation of the body. The biological, linked to the digital, is formulated in quantitative terms: degrees of variability, probability of normality, averaged diseased brains become so many new processes in a new form of evaluation of health and illness as a measurable set of factors—a topic to which I shall return below.

Brain mapping’s approach to biologically and digitally-based knowledge therefore contrasts with traditions of visual knowing, of research on the mind and of clinical examination of individuals. Automated image evaluation, quantitative anatomy and database diagnosis therefore pose challenges to existing clinical practices and to conventional imaging strategies, which are sometimes resisted by groups outside the brain mapping community. This leads not only to interesting negotiations and adaptations of forms and formats of brain mapping knowledge, but also to the touting of the benefits a shift to the digital, quantitative brain might offer—objectivity through quantitation, measurability of elusive conditions, and predictive diagnosis in advance of clinical signs. This tension is not limited to research/clinical interactions. Even in the study of the normal brain, the use of digitalised maps of the mind requires the adoption of different standards of evidence. Here too there are trade-offs between the biologisation of the mental, praised as a grounding of cognitive science in the materiality of the brain, and the constraints of working in a digitised setting, within the limitations of scanning technology and experimental strategies. How a digitised and biologised approach to the mind and brain becomes an accepted scientific practice is a complex process of hybridisation and exchange between technoscientific cultures.

Digitalisation is a dynamic common to other scientific endeavours, as computer visualisation and other forms of cyberscience become increasingly widespread. Insofar as these will be multidisciplinary and will be focused on ideals of integration and rationalisation of research, brain mapping and neuroinformatics form useful cases studies of this process. Yet, the case of brain mapping also presents some particularities in contrast to other projects, about which I wish to reflect. Some of these particularities will show how digitalisation may take different forms, for example, depending on the extent to which all aspects of knowledge production will be involved, or the significance that visualisation will take. These contrasts should further highlight the importance of a contextual approach to the study of digitalisation, as well as emphasise the conditions that have led to brain mapping taking on such a thoroughly digitised form. I will also suggest that some of the differences between this and other comparable mapping or databasing projects may very well have to do with the particular entities with which brain mapping is concerned; in important ways, the biologisation of mind is the biologisation of the self.

167
Kinds of Digitalisation: Pipelines and Bureaucratic Organisation

The particular approach to databasing of the brain mapping and atlases emphasises ‘pipelines’ and standardised conventions. From data acquisition to ‘final’ visualisation and modelling, all steps are carefully coordinated, between instances and participating groups. The thorough dominance of Talairach space illustrates this coherence of standards (See Figure 2, page 8). If there are important and interesting exceptions to the adherence to these conventions in practice, standardisation and uniformity are nevertheless ideals that are intensively pursued. This level of standardisation can be contrasted to other projects, such as the Cochrane Initiative. This endeavour to promote ‘evidence-based medicine’ uses results of clinical trials, mostly published but occasionally unpublished, in order to build a database of the scientific evidence underlying medical treatments. The ‘randomised clinical trial’ is the ‘gold standard’ definition of what types of results count as ‘evidence’. Accredited groups partake in meta-analyses of reports on various treatments and drugs, and their results are incorporated in the Initiative’s publications and libraries.

In comparison with the atlases and databases of the HBP, this constitutes a post-hoc, centralised analysis. While the atlases have to reckon with the specificity of their conventions and the rigidity of analysis pipelines, the Cochrane Initiative can ‘use’ the work that is already going on in the field, but it has to contend with criticisms of its efforts to analyse results across time, space, labs, and institutions. Some epidemiologists argue that meta-analysis is not feasible without at least consultation with the researchers who conducted the research (Taubes, 1996). So while the Cochrane Initiative does make use of digital and electronic resources for searching publications, setting up collaborations and communicating its results, this is a very different kind of digitalisation of research. The ideals of the Cochrane initiative are also to rationalise and integrate data, thereby adding value to research done through meta-analysis (See The Agendas of the Decades of the Brain, Neuroinformatics, and the Human Brain Project, page 137). But here, we have two dramatically different modes of achieving trust in evaluating data; face-to-face interactions or faith in experimental design, versus automation and standardisation. Part of this contrast can be explained by the clinical settings of the development of new therapeutics treatments and of clinical trials, where, as seen in chapter 4, judgement is required to evaluate which factors might matter or not. Neuroscientists rather aim to formulate and enforce the features of brains that might make a difference. A further fundamental aspect of this contrast is the deep embeddedness of digitality in brain imaging data. Clinical trials rather have as outcome a ‘number’, indicating a statistically significant effect, or its absence. The use of electronic and digital resources can therefore take on many forms; clearly brain mapping and neuroinformatics constitute some of the most innovative and novel approaches to building knowledge, in terms of disciplined and bureaucratic management of data—reaping most benefits of digital objectivity in the process.
Other projects also display this deep embeddedness of digitality in ways of gathering data and working with it. Fujimura and Fortun note such discussions in the field of molecular biology where the increasing use of software and computational tools is discussed as a paradigm shift. For some biologists, this is taken to mean that molecular biology is changing from an experimental science to a technological one (Fujimura and Fortun, 1996). Similarly, the Visible Human Project is based on data acquired and manipulated in digitalised form. This form of knowledge too has been hailed as a radically different way of knowing: "The Visible Human Project is one of the more spectacular instances of a particular technical/epistemic moment—a moment succinctly described by Haraway as the 'translation of the world into a problem of coding'—which is well in train in fin-de-millennium culture (Waldby, 1996b)." For both of these projects, there is a shift to what Fujimura and Fortun (1996) call a "dominance of representation" based on databases. Coding and manipulation of code (as voxels or letters in a sequence), which thoroughly shape ways of working, constitute a particular, but growing mode of what I have been discussing as digitality.

Sampling, Variability and Individuality

In spite of these similarities, other aspects of the digitality of the HBP becomes all the more intriguing when compared to these other contemporary, internationally-oriented biomedical endeavours. This has to do with data sampling and gathering, but not in terms of its 'raw' or post-publication status discussed above. In the work of the International Consortium for Brain Mapping (ICBM) for example, large-scale sampling is a central feature. Hundreds, probably thousands, of brains will be entered into the Consortium's databases. In contrast, the Visible Human Project has at present 2 bodies in its dataset, the Human Male and Female. These datasets are made up of large numbers of images of 'slices' of the body, achieved using a number of technologies (CT, MRI, and digital photography). Having obtained these vast amounts of data, the National Library of Medicine is contracting bioinformatics firms and researchers to develop ways of integrating the various types of data and of manipulating and visualising this data. Officials hope that the data will be used to build atlases of heretofore unknown precision and detail, and provide a highly complete view of anatomy through the integration of these various imaging technologies. Furthermore, the digital format of this data will enable modelling and visualisation, for educational and research purposes. Here too, we find echoes of the goals of the HBP and of neuroinformatics.

But, most intriguing is the sample required for this project. With two specimens, the NLM presents a valid, representative account of human anatomy--with the important

---

181 There is an ongoing project to transform the brain of Visible Male to a Talairach style map (Drury, Heather and Van Essen, David, 1997).
caveat of reproduction and sex. While sex was the first difference to be included in the atlas, the developers acknowledge the possibility of including further variations:

"Of course, after you've done other races, ages body builds, then you start talking about pathology and that's tough because pathologies are so different" (Gershon 1996).

But these differences seem complementary rather than fundamental to a knowledge of human anatomy. The multiplicity and variability of anatomies are not of prime concern as they are in brain mapping and brain atlases. What mattered for selecting specimens for this atlas was that the specimens would die in healthy condition, and that their bodies would be available for imaging and processing in the shortest possible delays after death. Furthermore, the pictorial form given to most of the data in this project, and the importance of visualisation are a further contrast to the HBP. While both approaches rely on the particular manipulations that are possible with digital data, the quantitative aspect of digitality is not exploited to the same degree. The visual, observer-based traditions of anatomical knowledge are likely a significant factor shaping this orientation.

The Human Genome Project's sampling is also radically different from that of the Consortium. The human genome's results have been described as the map of a hypothetical person, a standardised model who corresponds to no one, but is derived from the tissue of thousands of donor bodies (van Dijck 1995). Thus it might seem that this project's sampling resembles that of atlases because it will examine thousands of specimens. But instead of being carefully catalogued according to a number of features as discussed in chapter 5, the genome to be mapped is indifferently anonymous:

"The ultimate genome map, Fink explains, will be a sort of composite; people are 'for 99 percent' similar in their genetic make-up, and 'because these small

183 Nicknamed 'Adam' and 'Eve', the pair represent the main variation of the human body—that is variation in terms of sex. But the presence of a male and female have not been quite enough to ensure representativity, and an interesting double standard has become manifest in the evaluation of the suitability of these bodies. Many have taken exception to the post-menopausal status of the female cadaver while there has been little discussion of the uni-testicular state of the male.

184 Waldby (1999) examines this and other paradoxes in the Visible Human Project. The fact that the availability of the male body is based on a "legal homicide" was also the subject of media attention.

185 The NLM has taken on responsibility for providing a dataset, while the development of tools for visualising and 'navigating', for turning this dataset into an organised database, has been left to various entrepreneurs.

186 Van Dijck (2000) explores other aspects of the continuity of the Visible Human Project with anatomical traditions—among these, the use of the bodies of criminals.

187 When objections are made to the HGP, these mainly address issues of privacy, efficacy and reductionism—not objections of the type levelled against the Talairach framework of brain mapping—"this is based on the single hemisphere of the brain of one French woman."

188Lock quotes Lewontin “the human DNA sequence will be a mosaic of some hypothetical average person corresponding to no one and polymorphism (within-group genetic variation) will be ignored (Lock, 1997)."
difference carries from person to person, it does not matter whose genome it is."
(van Dijck, 1995).

While brain atlases will also be ‘composites’, they will be a very different kind of composite. Different brains will be brought together, not as in the case of the Genome, because it doesn’t really matter which is used because they are so similar, but on the contrary, because sampling across kinds of people is considered essential, in the most literal sense of the term, to knowing about the cortex.

There are of course notable exceptions, within larger scope of the Project and the field of genetics. ‘DNA fingerprinting’ is all about identifying individual humans on the basis of their genes. And in one particular component of the project, being of a different ethnic group is considered to be one of the differences that are assumed to make a difference—a highly contested assumption of the Human Genome Diversity Project. But in spite of its composite nature, the human genome is a singular object to be decoded, the book of Life, and not of lives. Brains are mapped and atlassed, on the contrary, on the basis of carefully selected, purposely average randomised individuals, whose brains have been marked for a wealth of features besides (but including) race/ethnicity, such as sex, age, handedness and a non-pathological, super-normal past.

A further point of contrast is that the genes sequenced in the HGP need not be ‘human’:

“Many genes work in the same way, regardless of the living being in which they are found...this ‘genetic code’ has not changed during evolution and, therefore, many genes of simpler organisms are basically the same as human genes (Rabinow, 1992). “

While other species are also considered in the HBP, the possibility of studying the human brain constitutes one of the key features of these endeavours. The higher functions are only apprehensible in the human cortex-- that most evolved of structures. Furthermore, as discussed in chapters 3 and 5, the greatest variability in structure and localisation is also associated with these higher functions. Decisions about sampling and gathering data in the HBP and neuroinformatics are therefore closely linked to features that differentiate us from other species and which are related to features of our selves.

[189] In this project, endangered ethnic groups are targeted for collection of blood samples, in order to preserve a ‘disappearing’ genome. “In contrast to the HGDP, the HGP has capitalized on this lack of variation in its efforts to create a ‘map’ of what will be the human genome, an endeavour described by one biological anthropologist as ‘ill-conceived essentialism’ (Lock, 1997).”

171
Kinds of Biologisation: The Dimensions of the Mind-in-the-Brain

The particularities of knowledge structures and representations produced in the course of the HB project can therefore not all be attributed to the extreme digital form that this project has adopted. It is the biologisation of self and individuality which is involved in the making of these new representations. The objects of all this data-acquisition are also determinant of the shape these representations take; the brain and mind are the sites where human potential has been inscribed. I want to briefly sketch two of the main assumptions about the brain which shape the biologisation of mind, with a special focus on how these interact with processes of digitalisation.

Evolution

The first set of assumptions relate the study of the cortex and evolutionary theory. The significance of these was unexpected, but arose again and again in the course of researching the various aspects of brain mapping. In the conception of anatomy and variability, the significance of being able to image the cortex (and especially the frontal lobes) was subtended by its status as the most recent structure, evolutionarily speaking. Similarly, in analysing the experimental methods for subtraction, hierarchical notions about the complexity of functions were also organised according to an evolutionary logic. Higher functions (=more recently evolved) produce more subtle activations than the robust sensory and motor functions, requiring subtraction, and the highest of the higher functions required even more complex modes of subtractions. Activations showing networks that recruit the frontal lobes were also taken to be indicative of a higher function. Recall also that the very mode of localisation of functions in the brain (systematic versus idiosyncratic, as in the study on bilingualism) was explained in terms of evolutionary advantages. All these hierarchies are warranted by an evolutionary logic which turned out to be significant in the brain mapping approach to the brain.

While the cortical hemispheres are only one of the main parts of the brain (along with spinal cord, medulla oblongata, pons and cerebellum, midbrain, diencephalon), the cortex is treated as the crowning glory of the brain’s anatomy—the result of a hierarchical view of the brain’s Darwinian evolution. There are portions of the cognitive and neural sciences which treat the brain as a more integrated whole, which incorporates the hierarchy (Schmitt, 1978). But cortical localisation and notions of ‘encephalisation’ and its measure remain organised around hierarchical notions of the brain and its functions. For example, in “Comparing Brains”, Harvey and Krebs (1990) state the general principle that differences in encephalisation are associated with diet in mammals. Difference in encephalisation arise through variation either in the range of stimuli that need to be processed for feeding, or in the associated information storage and retrieval systems rather than the nature of the food resource, among other factors. The principle can be restated as the existence of a relation between the complexity of tasks and size of brain. Humans, in these hierarchies, are the most encephalised animals. A more complex brain related to more complex tasks is therefore the basis for humans’ (measurable) distinction from other species.
Similar arguments are made specifically about the cortex and its growing size over the course of evolution, as humans take on more and more complex tasks. The folds in the cortex are therefore considered to be an evolutionary strategy for augmenting the surface of the cortex (Kandel, 1991).

Recall that it is the variability of these folds that make generalisations about localisation of functions particularly difficult. Evolutionary achievement leading to abilities particular to humans are therefore to be found in the particular structures of the cortex.

**Uniquely Human**

Evolution orders functions and structures, and humans as the most evolved are also unique bearers of these. The preceding chapters have made clear how these higher functions came to be studied in brain mapping as experiments, brain scanning technologies and representational conventions developed. Having examined in detail the shifts towards reductionism that these developments involved, I wish to emphasise here the significance of these associations which produce the mind-in-the-brain, at a conceptual level. The following paragraph (setting out the research program of the NSF: Division of Behavioural and Neural Science) collapses these elements of the uniquely human mind onto the brain, establishing as a starting point the biological basis of behaviour and its investigation through brain mapping technologies:

"Another term for this complex of cognitive processes that are in many ways uniquely human is ‘mind’, which is not to be taken as some mystical entity but rather as a description of the functional properties of our brains that render us human. Thus the study of human cognition and perception is in a very real sense the study of the functional properties of the human brain... One aspect of the study of human cognition and perception is the use of various non-invasive techniques, such as PET, MRI, ERP and MEG to discover the neural correlates of human cognitive and perceptual activity (NSF, 1991)."

This line of reasoning which equates mind and human brain functions, locates them in the brain, and points to the privileged access provided by brain mapping technologies is a widespread theme in the Decade of the Brain. Variations on this theme abound. A very prominent neuroscientist began an introduction to a special issue on the brain in the following manner:

---

190 This explanation is given in terms of the limitations for ‘straight’ increase in size: the cortex cannot simply grow larger, because there is a ‘limit’ to the size of head that can be born. Discourses of cortical folding and encephalisation in evolution are also echoed in fascinating ways in developmental explanations: the development of an embryo’s brain retraces evolutionary changes. See for example Swanson (1995).
"...what makes man human is his brain. His humanity includes those aspects of
behaviour traditionally classed as mental.... Things mental, indeed minds, are
emergent properties of brains (Mountcastle, 1998)."[19] 

There is yet another element to be tied in here—not only what distinguishes ‘man’ from
other species is to be found in the brain, but also the basis of what distinguishes humans
from each other. Recall the theories about cortical folding, and the notions of
idiosyncratic localisations discussed in chapter 3. Pursuing this line of reasoning,
Mountcastle, quoted above, ends his introduction with a number of foundational
principles of neuroscience among these, “the individuality of individual brains”. The
individual mind can then be related to this view of the mind-in-the-brain, through notions
of the individual, as a sum of factors which can be traced, measured and managed based
on knowledge of the brain.

While there are many difficulties in achieving this goal, as seen in the discussion
of the production of atlases, differences in the brain can, in principle, be mapped to yield
insight about individual differences:

"...variability in gyral and sulcal patterns—as anatomically distinct as
fingerprints—may not present so much an obstacle as a means of distinguishing
neural profiles pertinent to interindividual differences in cognitive, motor and
perceptual capacities (Jouandet et al. 1989)."

The amount of attention focused on the cortex and its variability in the creation of these
representations is therefore warranted by the assumptions that these differences must be
significant, or eventually shown to be significant.

The most recently evolved part of the brain, the cortex, is therefore the seat of the
higher cognitive functions, and part of the evolutionary stories that are more and more
often being told in science. Underlying the approach of brain mapping to the mind-in-the-
brain, and more specifically, to individuality-in-the-cortex, are assumptions about what
warrants our status as different from animals, as well as assumptions about what
differentiates us from each other as individuals: the cortex as the very seat of our
humanity and individuality. Given that these concepts are loaded onto the brain, the
appeal to the quantitative possibilities of digital approaches can be understood as an
attempt to build this new knowledge about traditionally lofty concepts (mind, self) and
politically loaded issues (human potential, biological determinism) in a framework that
establishes scientific neutrality and objectivity.

[19] Chapter 5 contains a discussion of the ways in which the individuality of the brain, (rendered
problematic by having the individual’s identity loaded onto to it) is accounted for in studies across brains of
populations.
Bounded Brain

While the mapping mode of knowing about the mind-in-the-brain focuses on the material, as rendered quantitatively, the ‘symbolic’ is neither automatically nor entirely evacuated with the use of numbers. Quantitation is not only a way of working with data, but has also been observed to take on what might be called an iconic role. After analysing three ‘facts’ about neuroanatomy (cortical connectivity resources, cortical sheet area, and synaptic density), and finding wild discrepancies in the numbers given, one author calls for more rigour in the use of quantitation in relation to the brain. He attributes these inconsistencies to the extension of a Cartesian view of mind (which has neither spatial extent nor physical limitations) to the brain (Cherniak, 1990). Interestingly, he also observes that the use of certain figures (billions, etc) might be understood as more than sloppy science, and function as a kind of formula for invoking wonder for the brain:

“The issue can be couched as the question of what is the essence of personhood or humanity, traditional answers including rationality, the capacity for language, or a type of functional/computational organisation. We can now add another candidate for an answer, that human beings are quantitatively distinct—it is our unbounded complexity of mind and brain that is unique, that puts us on top. What is at stake here is not only the analytic matter of what it is to be a person but also what it is that gives persons any distinctive moral worth. This is not just species snobbery but rather a matter of preserving our distinctive moral value in view of a perceived encroachment of the naturalistic view of the universe and our species’ place in it. In such a context, quantitatively romancing the brain is understandable and in a sense admirable....”

Though understandable, this exaggerated view of the brain it is not scientific, and he maintains his call for a rational approach to quantitation of brain anatomy.

In other ways, quantitation does mark a particular way of knowing which attempts to evacuate the symbolic and iconic aspects of anatomy. This can be observed in the redefinition of anatomy in brain mapping. Beginning with the early adoption and adaptation of Talairach discussed in chapter 2, to the development of programs for translation (Braintree) from anatomical names to coordinates discussed in chapter 5, there is a significant shift to a quantitative understanding of the brain’s anatomy. This shift marks the departure from what have been termed “modernist” concepts, which have traditionally shaped the linguistic constructs of anatomical nomenclatures. The x,y,z locations defined by numbers form a sharp contrast to the linguistic ordering of the brain’s space, itself associated with a skilled observer. But this new quantitation is not for use in a Euclidean space: the x, y, z brain is most useful in a digital space:

102 See Edgerton for a discussion of a contrasting case, where the artful skills of many scientists, involved in observational sciences, are argued to be key elements in gathering and representing new knowledge (Edgerton, 1984). Recall also the failure of photography in 19th century systems of visual classification, blame on the untameable wealth of detail of the optical image—a wealth of detail unmanageable to the observer. See also footnote 115 on the observer.
"If to be a modernist meant constructing a formal vocabulary that was clean, streamlined, in which representations looked abstract and were reconstructed from geometrical forms, to be postmodernist implies the figure/ground ambiguity of virtual reality and the intertwining of hypervisible collage (Stafford, 1996)."

In a digital grid, quantitative anatomical locations can be intertwined with other kinds of data, and this might be called collage. Arguably, however, there is a different kind of cleanliness to virtual reality. As suggested at the beginning of and later demonstrated in this thesis, though digitality explodes representational possibilities, this does not mean that all and any options are equally acceptable. There is no suggestion of loss of scientific rigour in quantitative anatomy, but rather a shift to different ways of disciplining data and authenticating knowledge. The key element in this shift is the claim that this way of knowing does not rely on symbolic, literary or esthetic sensibilities and fulfils the highest standards of objectivity.

Normality by Numbers

Digitally knowing the brain-in-the-mind therefore provides a particular solution to the problem of representativeness, the epistemological problem of having recourse to the ideal or the typical to represent a class of phenomena. Brain mapping and neuroinformatics offer quantification and automation as solutions to this problem. Furthermore, these ideals propose to solve the difficulties in applying these norms, also ensuring the unbiased application of quantitatively derived standards of normality. Again, the contrast with traditional atlas representations is fruitful. Waldby observes that

"in both cases [the typical and the ideal] anatomical forms of representation involve standardisation along particular lines which allow the single image to stand for a class of objects. Standardisation in turn can only be made outside the frame of the representations themselves, in the sense that no purely quantitative, statistical process can average out, in the sense of flatten out, morphological idiosyncrasy. There can be no neutral process whereby all natural variation can be condensed into a single image or even a series of images. Condensation always involves judgements about what counts as normal, judgements which precede the process of condensation itself (Waldby, 1996a)."

While the point remains that one must go beyond ‘the series’ and look at the a priori criteria that shape the selection of normal instances, these new representations and the tools to create them have been developed with precisely the aims of averaging out and condensing all natural variations. Furthermore, it is in effacing normative judgements and decisions that underlie these representations that brain mapping tools are so efficient. The quantitative digitality built into these tools and practices lend a guise of neutrality and rationality to the parameters of normality that emerge in these new representations. It is

176

195 This problem has been discussed empirically in chapter 5. Waldby (1996a) also identifies this issue, in relation to representations of pathology, specifically the case of AIDS.
also by invoking the power of the statistical and quantitative that, what are after all identity categories (age, gender etc), shift into neutral features of brains.194

Metaphors of the Mind-in-the-Brain

Before discussing the notion of a material science of self to which the embodiment of these features point. I want to end this section on the biological notions involved in brain mapping by signalling the metaphorical state of the mind-in-the-brain. Specifically, I want to highlight how the growth of digitality in relation to biological knowledge gives rise to hybrid concepts. For example, the mind-in-the brain is a term I have used to highlight the shifts in cognitive and neuroscience and claims about these shifts. Insofar as no single location in the brain is responsible for a function, these maps of the brain emphasise a networked organisation. But more complex functions are assumed to involve equally more complex configurations of areas, so that a hierarchical element is introduced. Furthermore, some areas are considered to be typically involved in higher functions, such as the frontal lobes. Stories of evolutionary development further embed these areas of the brain with more recent development and higher human abilities. The mind-in-the-brain is therefore both a network and a hierarchical, organismic entity, joining two of the dominant metaphors of twentieth-century biology.195 A further investigation of these metaphors as they arise in brain mapping would indicate whether this mixed metaphor is a temporary occurrence or whether it is being built up as a new, viable configuration to denote the mind-in-the-brain.

194 Like Waldby, I link these questions to a feminist approach to the body which asks, in Butler’s terms: ‘[what are] the political stakes in designating as origin and cause those identity categories that are in fact the effects of institutions, practices, discourses?’ (Butler 1990).

195 Discussions of pathology provide further examples of this mixed metaphor, where both organ/organism and network co-exist. Many current clinical interventions retain notions of targeting of specific areas, where therapeutics is informed by a logic of excision of pathological tissue—a view of the brain established in the work of neurosurgeons such as Penfield, and experimentalist such as Hubel and Wiesel. In the 50s, the brain was a territory with strategic points, and pathology of an enemy brain could be disarmed by striking at that weak point. One’s own mind could also be colonised, captured, invaded. A sick brain was a brain separated from the body, an organ out of balance and powerless to resist the whims of the id or superego, misusing its powers of telepathy or telekinesis (Sconce, 1995)—the brain as agent forcing its strength onto another. Narratives about the brain in the nineties reflect a different view, where the brain is a network, and where danger (or genius, bordering on madness) lurks in overly networked minds-in-the-brain. (I am here thinking of films from the past decade such as Lawnmower Man, The World is Not Enough, Phenomenon, or even the Borg collective from the science fiction television series Star Trek). Weaknesses and breakdowns in the brain are similarly not phrased in terms of weak points in a territory, as when the brain was investigated using electrical stimulation mapping. Rather, they are disconnections in the brain, lack of pathways or over-recruitment of certain area into a network. (There are examples of this in research on schizophrenia, which investigate the development of particular pathways in ‘children at risk’, or the non-suppression of certain auditory processing areas in schizophrenics processing speech). Recall as well the criticism of mapping as rendering the brain as a territory, and not being able to fully render with brain mapping the network view of the brain.
A Materialist Science of Self?

Cartesian notions of a mind-brain distinction have traditionally been deeply embedded in definitions of self, where identity and especially, individuality were features of the mind. As individuality is operationalised as a set of brain features, evaluated neutrally and objectively through powerful digital tools applied to the brain, a material basis for the self comes into being. Such a re-articulation of the mental and physical domains constitutes an important shift in the cognitive and neural sciences, with significant implications for social and cultural institutions that have also been aligned to these domains. These definitions become implicated in cultural desires for health and self-improvement (Dumit, 1997), but also in anxieties about possible unwanted interventions. Earlier claims of mastery of mental function gave rise to a particular genre of brain films in 1950s and 1960s culture (Sconce, 1996), expressing cultural anxieties and resistance to this potential dominance. These film narratives of evil brains and of assaults against the normal, human mind are analysed by Sconce as a rejection of the totalising discourses of intellectualisation and hyper-rationalism, in conjunction with an estrangement from the body:

"Brain films unleashed the awesome power of the mind only to contain it. They rehearsed the anxiety of a subjectivity besieged by mental science only to restate emphatically the strength of human identity. In the end, the conquering brain always falls in defeat, and in doing so, signals a victory for the individual subject, both as a political citizen and as a metaphysical category (Sconce, 1996)."

Such fears are far from being marginal or from belonging only to mid-century sensibilities. Anxieties in the nineties were also linked to ongoing scientific developments, just as electrical mapping of the cortex fed the anxieties of the narratives analysed by Sconce. But, with this most recent wave of brain mapping, it seems to be an overidentification of the mind with the body that fuels current objections. As a new project to map the mind-in-the-brain is in full swing, the perception of a resistance and fear of brain control on the part of the scientific community are sometimes noted by brain mappers (Frackowiak, 1998a), and have even led to an editorial in Science, which deplored the following apprehensions and their paralysing power:

The brain, however, occupies a particular exalted and revered niche in the hierarchy of organs of study. As a result, many are repelled by a reductionist approach that has proved so successful in understanding other organs of our bodies. The unexpected and counterintuitive is amusing when it involves the curvature of light or weightlessness in space, but it is not greeted with detachment when it is uncovered in areas such as nationalism, aggressiveness or competitiveness. Some are repelled by the idea that we can use education or medicines to overcome basic instincts. Others are unwilling to accept the idea that some instincts are anachronistic..." (Koshland, The Dimensions of the Brain, 1992).
Brain mapping, I have argued, constitutes exactly the kind of research mentioned in this editorial, articulating the relations between such behaviours, traits, or instincts and the brain. Furthermore, the technologies that are used to constitute these relations are also perceived as potential instruments for intervening in these relationships, by enabling the circulation of these claims (as maps) beyond the research domains and by serving as tools to test these relations.

A Factored View of Health

The mind-in-the-brain as the sum of factors, apprehensible within a material framework in brain mapping, therefore constitutes individuality in terms that resonate with current trends in institutionalised biomedical intervention. Castel asks the following:

"On se demande en combien de morceaux l'objectivisme scientifique pourra découper un sujet que l'on créditait, il n'y a pas si longtemps, d'un inconscient, d'une histoire et d'un projet...(Castel, 1981)."

One is led to wonder about the extent to which scientific objectivism will slice up the subject into discrete parts--a subject which, not so long ago, was still endowed with an unconscious, a history and a life project [my translation].

The answer for brain mapping: "en autant de morceaux qu'il n'y a de sillons... in as many slices as there are sulci". This reply should not seem entirely facetious, since these folds in the brain are arguably as distinct as those on the tips of our fingers, and as we have seen, are invested with great meaning in the course of brain mapping. In other words, these folds, along with the other emerging concepts analysed in this thesis, are the differences that make a difference, and constitute the set of (biological) factors that place the mind-in-the-brain in the field of interventions on the body.

The dynamics leading to this type of reductionism have been analysed for other projects in the biomedical sciences. Rabinow, in the case of genetics, and Castel, whose work focuses on psychiatry and psychoanalysis, demonstrate the move away from contextualisation and towards and instrumentalized approach to the individual and its environment, constituting these as the sum of diverse factors to be analysed by specialists

196 These anxieties sometimes focus on an invasion of the private world:
   "I found myself imagining the impact [functional imaging] could have had on the perpetrators of the Spanish Inquisition, and on others of that nefarious ilk: they would no doubt have desired that the technique be developed to the point where one could read a person's actual thoughts, that ultimate violation of privacy will surely never be possible. But then again, never is dangerous in science (Cotterill, 1995)."

197 While I argue here that this way of knowing about the mind is new, there have been other moments in the history of the sciences of the mind where materialist approaches have dominated. Commentators have attributed shifts away from these approaches to the 'descent' of Phrenology and anatomy into bourgeois materialism (Sappol, 1997; Colbert, 1998), or the rejection of the overly holistic view of functions that were localised (for example, 'benevolence') (Kandel, 1991).
(Rabinow, 1992; Castel, 1981). For Rabinow, the end of modernity is signalled by the
dissolution of the category of the social into that of nature (Rabinow, 1992), a dynamic
that describes well the study of bilingualism discussed in chapter 3. Other analyses
(Haraway, 1991; Waldby, 1996a; van Dijk, 1995) have pointed to the significance of
discourses of immunology and genetics in expressing human potential. But whereas
immunology and genetics keep a door open to the unknown powers of the environment,
brain mapping makes these into factors that can be encompassed by scientific
investigation. As such, the nature/culture distinction is arguably blurred to a greater
degree by the integration of culture, development and experience into maps of the mind-
in-the-brain.

At a societal level, these processes are the result of changes in social technologies
that minimise direct therapeutic interventions, in favour of a system that focuses on
prevention, and the promotion of the need for self-improvement, at the level of the
individual (Rabinow, 1992; Lippman, 1992; Nelkin and Tancredi, 1994). A number
of practices therefore co-exist; at one end, the management of social risk by the state, at the
other, the work that befalls the subject in order to deal with the management of individual
frailties [les fragilités individuelles] (Castel, 1981). In terms of the body political
implications of this kind of knowledge, I would emphasise that the effectiveness of these
systems is greatest when there is a common vocabulary to name these risks between the
institutional level and that of the subject. The visual element that endures in the digitality
of brain mapping may be just such a way to establish common ground. Digital
representations of illness and ability, concretely and materially apprehended in the brain
circulate all the more easily from research to medical to public contexts (and back again),
for being both visual and scientific. In the case of brain mapping, therefore, these two sets
of practices (institutional and individual) are based on the same representations that
convey, albeit in different ways, these factors that make up healthy or sick selves.

Whether representations which combine both digital and visual form are
particularly powerful and effective in circulating is a question deserving of further
systematic investigation, of the type that has been pursued for other forms of
knowledge.108 Using the present case as a guide, such studies might be set up by
examining the circulation of digital representations between epistemic cultures. The
malleability of the digital, the possibility of a quantitative and visual understanding, could
then be systematically analysed, and related to features of these epistemic cultures. The
case of brain mapping points to the following as likely to be determinant of the epistemic
value to be given to these representations: ideals of objectivity held by a group, and its
investments in the potential use of machines for measuring and eventually ‘testing’, its
systems for cascading representations and giving added value to increasingly complex
representations. A further point of analysis, perhaps more difficult to operationalise,
involves the meanings attributed to the entities being represented. In this case, the shift
form mental to material in the formulation of the mind-in-the-brain has many
philosophical and political implications. Such momentous category shifts might not arise

108 The following come to mind: Porter (1996) on quantitation; Daston (1992), Dehue (1997) and Hacking
(1990) on statistical knowledge.
in other instances, though the effects of digitalisation will rarely be insignificant, if only because of the ease and degree of circulation to which digitised representations are amenable.

While such an endeavour seems to me eminently promising, comparable projects having already yielded significant insights into the study of experiments, laboratories and popularisation (Galison, 1997; Knorr-Cetina, 1999; Beaulieu, 2000), further reflection on the basis for comparing cultures would be necessary. 'Science and technology studies' have at times been accused of reinventing the wheel, by reformulating insights already well-developed in other spheres of the social sciences and humanities. 199 But before embarking on the project I sketch above, the experience of anthropology might be considered. The stream of 'comparative cultures' studies specifically might be explored as an important body of knowledge, regarding the limitations of such an approach. 200

Representations in Science and Science as a Representational Practice

Finally, I wish to raise the issue of representation as an analytic concept. In the first chapter, I argued that representations are a key element in brain mapping, in the same way that detectors can be point of entry to analyse the culture of high energy physics (Traweek, 1988) or that sexual categories are indicative of the concepts of immunity and AIDS in biomedical culture (Waldby, 1996a). This kind of analysis, based on a recurring motif which shapes the logic of a culture and provides the analyst with a 'handle', is part of the tradition of symbolic anthropology. Are there any particular issues that arise in having representations play this role? The argument has been made that rather too much was being made of representations (Lynch, 1994). The fear, arising from an ethnomethodological corner of STS, seems to be that representations are too often considered ready-made and self-explanatory, transparent windows on scientific practices. Lynch signals that once representations are selected as elements for analysis, the problem of defining a relevant context for understanding 'representations' is just as complex as that of defining, for example, the relevant context to understand a 'work':

199 Such a dialogue seems to be occurring in some parts of the STS community. See special issue "Anthropological Approaches in Science and Technology Studies," STHV 23(1): Winter 1998.

200 Consider for example the following reflection on 'relativism' and the anthropological stance:

A principle characteristic of the Other, then is that he is incapable of recognizing otherness. In the modern anthropological perception of the alien Other, he is—as Foucault says of the madman—Different only in so far as he is unaware of Difference. The principle characteristic of different cultures, anthropologically conceived, is their inability to recognize difference, as we do, their own relativity. Our knowledge lies in the fact that we recognize, not, as in the Enlightenment, our ignorance, but rather our relativity: our relativity and their relativity, whereas their ignorance lies in their cultural absolutism (McGrane, 1989).

Recast in terms of epistemic cultures and objectivism, this analysis can inform the STS scholar on the concepts of casting scientists studied into an Otherness that portrays them as rigidly objectivist practitioners of science, and allows them one sole script, that of single-minded pursuit along their chosen path to truth. A productive reflexivity on the part of the analyst might then subtext the approach to various scientific cultures.

181
"Assuming that not all analytically definable elements of the ‘heterogeneous field’ apply equally or all at once, a would-be critic is left with the problem of specifying how the work under analysis expresses, or otherwise exhibits, the relevant contextual relations (Lynch, 1994)."

Too narrow a focus on representation therefore means ignoring the local production of meaning. This should indeed be avoided—but a critique of the artificiality of the boundary between text and context need not end up with the collapse of one unto the other and with the evacuation of all views of science except its definition as ‘text.

While this criticism is important, both theoretically and politically, the underlying assumption must be examined. Lynch assumes that “the critic is unwilling, simply to stipulate, on her or his own authority, what counts as the relevant context (Lynch, 1994).” A number of responses to this objection are possible. First here is nothing simple about analytic authority. Second, such a move, when properly conducted and accounted for, surely cannot be in and of itself more arbitrary than the hundreds of other decisions with which (even the ethnomethodological) analyst is faced. Furthermore, this move is not repugnant to the symbolic anthropologist—though this stance may involve a more explicit construction of the analyst’s authority (…see Annex). This move further constitutes a particular form of empirical exploration, one which repeatedly challenges the analyst to reflect on the interactions of method and object. Non-reflexive fieldwork yields no data; its productivity is based on a healthy dialectic which, over time, weaves a solution to Lynch’s problem of “correlating ‘text’ and ‘context’.” The main role of fieldwork in the course of this project was precisely to investigate what might be the relevant context of an emerging set of research practices with fuzzy boundaries and sometimes chaotic interactions. In dealing with new scientific texts and contexts, (in having to look for the virtual lab, to name but one example), the analyst may be called upon to construct a different kind of authority, one fit for digital texts and electronic contexts. In a context where new modes of representations may increasingly be the way technoscience develops in the coming century, the analyst’s ability to postulate relevant contexts should be valued as a rich and dynamic critical resource. The observer is dead. Long live the observer.

201 See Lock (1997) for a further reflection on this issue, as applied to the (im)materiality of bodies in recent analyses.
Annex I. Being There

The following text has travelled to different parts of my thesis before landing here, but was originally the core of a ‘first chapter’. Its presence in an annex constitutes an indication of the archaeological layers of this thesis rather than a compromise or a rejection of its materials and insights—which indeed inform the whole of the research and writing that followed two periods of intense fieldwork. Part of the trajectory of this piece was shaped by my own local epistemic culture in which reports in the first person (me) and mentions of anonymous informers were repeatedly selected out for criticism and found to be more jarring than informative, more anecdotal than analytic. I take full responsibility for landing in the lab with a clinician’s visual interest in the particular, but a researcher’s universalising ambitions. So while claiming success for finding the right transformation algorithm for field notes in chapter 4, I also offer the text below as an account of formative experiences, the tacit knowledge that shaped my exploration of brain mapping literature here made explicit. The text falls into the genre of ‘arrival accounts’, personal narratives that are meant to “play the crucial role of anchoring, that description in the intense and authority-giving personal experience of fieldwork.”

Choosing the Field

The idea of doing fieldwork, of going into a lab was part of the project from the beginning. A senior STS researcher with whom I discussed my fieldwork, a pioneer of the first wave of lab studies, wanted to know what the motivation for going into the lab ‘could now be’ (Now that the constructed/ cultural nature of lab practices was established I wondered’.) It seems he wanted to be reassured that it wasn’t a question of seeking authenticity, the origin of knowledge, the search for the hardest case in STS. I was able to reassure him that that was not a primary motivation, and had more to do with a different kind of difficulty about this particular case (the high tech and pioneering nature of imaging) and with practical considerations (the lack of any secondary resources about the technologies or methods, my need to learn more neuroscience and my interest in keeping a link with Canada, where the lab to be studied was located). Understandably, this notion of authenticity seems to have been quite strong as a motivation, for that first wave: Knorr-Cetina has called this “touching the hard core (Knorr-Cetina, 1995). A slightly different version of this stance is found in Traweek, where she cannot resist noting in the conclusion of her study that she has done the hardest case, shown the culture of no culture: “I’ve shown how important a culture of high energy physics is in this group which seems to think it is acultural (Traweek, 1988).”

---

Pratt (1986) suggests that such accounts mediate between the personal and scientific authority typical of anthropological research and writing.
In spite of these similarities in the powerful drive to pursue these studies, further differences should also be noted between the more sociologically-oriented lab studies and those pursued, like Traweek's, in a cultural anthropological mode. Studies such as those of Knorr-Cetina (1981) and Latour and Woolgar (1986) tend to emphasise the fact that earlier lab studies have shown that there is culture inside the lab, just as there is outside, so that the objects (of knowledge) produced are also thoroughly cultural. In these analyses, the notion of cultural is made meaningful in its contrast to objectivity (guaranteed by reality, nature, or the scientific method). Anthropologists such as Traweek, Goodwin or Henderson (who studied physicists, archaeologists and groups of design engineers respectively) start from the assumption that there is a particular culture in a group (lab or field), specific to it. And while this culture does thoroughly penetrate work of the group, it is what sets it apart. Arguing a slightly different version of the cultural, Emily Martin has recently written about the anthropological approach to science, trying to suggest new metaphors for the anthropological stance that would contrast with the view of scientific cultures as sovereign (the “citadel” approach) and enable an anthropology of science in society (Martin, 1998). The rhizome image she puts forth maintains some of the holistic elements (science can spring up anywhere, as a whole organism), while the “string game” metaphor makes the scientific portable, interactive, reconfigurable—and definitely hard to pin down—perhaps impossible unless one becomes a player and owns up to it.

Methodological concerns astride, it remains that the ethnographic approach is perhaps also one of the few (remaining?) that allow for a coupling of romanticism and deconstructionism, the opportunity to take poeties and ethics on board in one’s work (See Clifford and Marcus, 1986; Clifford, 1988). A romantic aura still hangs around the ethnographic, though it is not based in a notion of cultural holism as some professors might fear: first year textbooks of anthropology are all about syncretism and post-colonialism these days. But rather, I would argue, it is being carried by the methodological reliance on the process of socialisation. The starting point of the uninitiated is meant to enable the researcher to move from stranger to tolerable member of the group. The researcher is enabled by this strangeness to perceive common-sense notions held by a group, to understand its shared way of inculcating and relying on particular values, and to detect the ways in which it may sometimes be acceptable to question these. Underlying the opportunity provided by such a learning process is a glimpse of post-modern innocence. Of course this is coupled with an awareness (soon acquired in the course of fieldwork if not already present beforehand) that one will have to plain old struggle with this barely forgivable innocence—labelled as incompetence by the natives in any case. But however partial and fleeting, this promise of a productive reflexivity is part of the attraction of going into the field.

Otherwise, this approach was also shaped by stories from the field gleaned from colleagues. I also took guidance from other ethnographic and ethnomethodological writings (especially Hammersley and Atkinson, 1983), which made me aware of notions

---

203 Knorr-Cetina’s more recent work, by the way, also tends towards that notion of the cultural.

204 Though how much more forgivable in a twenty-something female.
such as sensitising concepts, gatekeepers, natural time cycles, and positioning. These were also helpful in developing note-taking strategies and ordering the use of fieldnotes and field documents. I had a strong preference for note taking over audio or video-taping, which I estimated to be cumbersome and disruptive. Preparations also involved a three-day dry run in a local lab to get used to the physical and social demands of being in a place of scientific work. Also significant, for what was learned and how it was digested, was the fact that fieldwork was performed in foreign settings. This meant that the work was pursued extremely intensely over the course of several months, and that I was involved in no other academic activities during these periods. All along, I assumed that much of the material for the thesis would come from written sources and a study of the professional literature.

**Going into the field**

I was first exposed to some of the natural categories by which brain mappers organise their work when I attended a major gathering, the 2nd International Conference on Functional Mapping of the Human Brain. There was one major divide in the organisation of the conference, which was quite visible. The sessions were oriented towards, on the one hand particular divisions in neuroscience and neuropsychology (motor systems, sensory systems, higher functions) and on the other, sessions consisted of technical issues (data acquisition, data analysis, etc). These sessions were very challenging, trying as I was to function on all levels: paying attention to the scientific content of what was being presented, while attempting to gauge what the reactions of the audience and to note who the keynote speakers were and what was their particular institutional and technological affiliations (there was a debate between proponents of fMRI and PET raging at this conference). I was also amazed by the number and bedazzling aesthetic of the presentations, so different from the conferences I had attended: each carefully rehearsed talk of 12 minutes (3 min for questions) consisted of pairs of huge colour slides, presented to a large audience to the rhythm of about one pair a minute. It is a prejudice commonly held by social scientists that slides are typical of medical communications, but on these slides, the imaging results were very strikingly present (brains brain brains), and their sheer number exceeded anything I’d seen in art history classes or film/media studies conferences. Besides those huge communal oral sessions, there were hundreds of posters, divided along the same lines as the oral sessions. A “town meeting” during the conference also provided much material on the various factions and the divided opinions about the direction that future meetings and the “community” should take.

Based on reading the journals, the material gathered at this conference and a few lectures, I had chosen a number of sensitising concepts by the time I began fieldwork.

---

205 Up to the 1999 meeting, there were no parallel sessions at these conferences, which attract about 1000 participants—a decision justified by pointing to the insanity of the Society for Neuroscience Meeting (with thousands of posters) and the need to maintain unity in this budding community.
Besides the theme of the visual present since the beginning, I was interested in the interdisciplinarity of the large teams that are needed to run a PET scanner. Physicists, computer scientists, statisticians, psychologists, neurologists and psychiatrists all gravitated around PET centres where brain imaging was performed. The complex arrangements of these groups seemed to differ between labs, partly due to what I came to call the ‘little big science’ aspect of this research: no two scanners were the same, centres had different cyclotrons which enable more or less diverse radiopharmaceuticals to be produced and different types of research to be conducted, no two institutions were set up similarly in relations to hospitals or universities, and consequently no two groups received similar funding. Yet, in spite of this diversity, there were attempts in the field to organise this group ‘professionally’, by creating yearly meetings (the first held in 1995) and an association for brain mapping (by the spring of 1998, a membership list seems to have been created), and efforts to link a particular journal to such an association.206

The centre where I began my fieldwork was hailed, and promoted itself, as the first to be set up from the ground up as a brain imaging centre, and not constituted from amalgamations and collaborations between departments and institutions. With a clear eye to beginning its own research program (doing only blood flow activations with PET and fMRI), the senior members of the team and a significant number of junior fellows and support staff had recently split off from a large, hospital-based institution funded by the government, where ligand studies (as opposed to blood flow) were done. The centre had also received generous financial support (from what in the Netherlands would be known as the third stream), so that I imagined this might represent what a ‘pure’ set up for what a functional imaging might look like, an ideal case, an institutionally unconstrained articulation of what this new type of research would be about. During this time, about 40 researchers and support staff occupied a dedicated building, located in a thriving cognitive science and research community.

This lab was also unique in the availability of two scanners, PET and MRI, dedicated entirely to research (in other institutions, functional imagers must negotiate the use of the MRI scanners around the clinical scheduling of scans by physicians). PET images, which provide functional information, are generally overlaid on anatomical MRI scans. Furthermore, the MRI scanner was also being used in a functional capacity (fMRI). I was curious to see how the two technologies would co-exist; a bitter confrontation between proponents of PET and those of fMRI, as well as countless dire predictions for the demise of functional studies using PET (in favour of the safer and cheaper fMRI) had surfaced during the Conference I had attended.

I was also interested in seeing where and how the knowledge claims of functional brain mapping were being established. I hoped to trace the reception of functional imaging from the interactions of ‘outsiders’ with this centre that was located (physically and institutionally) in a hotbed of neuroscience. There were numerous potential opportunities for collaboration with a major neurological teaching and research institute, 206 By Spring 1999, this email list was regularly being canvassed on a number of issues, many concerning sharing of data and software (“interoperability”).
several other major hospitals, and academic departments of a university (psychology, cognitive science), as well as ties to a world renowned neurobiology lab. The centre also ran and hosted a number of lecture series with prestigious neuroscientists and psychologists, many of whom did not specifically work with imaging technologies.

Speaking of imaging...

Among the 5 foreshadowed themes, asking about images was by far the least successful part of my interviews. I did many of these in the beginning of the fieldwork, because I perceived quite a bit of nervousness (not quite distrust or anxiety) about my purpose in the lab. My presence and activities in the lab had been endorsed by the lab director, and some felt that my presence was part of what one informant later called “this lab’s unusual management practices, i.e. they’d put in a sociologist and throw back at us the information gathered”. The timing of my arrival a few weeks ahead of the lab’s ‘retreat’ seemed to fit with such a scenario. I hoped the lab members would be reassured when they realised that none of my questions were about ‘efficiency’ or productivity.

Whatever the results of my attempt at positioning myself (a process over which the fieldworker has very limited power), the questions in my interview scheme that dealt with the role of the visual evoked the shortest, most boring answers. The images, I was told over and over again, were simply the best way to convey a lot of numbers, a way to make the measurements more understandable than tables of numbers. I tried to get ‘more’ out of my interviewees by showing them images (for example, the ones I used when giving talks about my work on imaging). This elicited some comments on scientific communication, some of which could be linked to what I had witnessed in the conference. But this was a moderately successful strategy. In their responses my informants often named the “quantitative” as the true referent, the true object of their considerations: the visual about which I was asking was acceptable because it was all “really” quantitative. Such a treatment of the visual reminded me of the work of Lynch’s observations on the quantification of evidence. But mainly, the reactions puzzled me by their vehemence, and made me question the analyses of writers like Barbara Stafford, who indicated that there was a growing trend to accept images as scientific tools, and that such a trend showed the reversal of the hierarchy of image/ text/ number established since the birth of Modern Science. From listening to my interviews, I can trace how I backed off the topic, made the questions less direct, and often formulated it in ways closer to the perceptually-centred vocabulary of my informants.

Experiments

The beginning of the fieldwork was largely spent in the scanner control room when not conducting interviews or attending meetings in the centre. I planned to make my way around the building, but the scanning room was the most welcoming. It seemed a good place to begin: there was lots of activity going on, as opposed to the other rooms
and offices where people mostly sat in front of computer screens. It was in the control room that I began to hear about experimental designs, as the researchers told me how they had set up their experiments. Researchers would talk about how these experiments built on their past work, and often this evolution in their work meant seeking a further distinction between two processes. They would tell about how they tried to get subjects to perform as well and as uniformly as possible, how they went about recruiting and training them. The scanning protocols ("paradigms") were largely uniform, so many scans performed for so many minutes, while the numbers of conditions and subjects varied a bit from experiment to experiment. I also heard about and observed outside collaborators, to whom the constraints of brain imaging had to be explained.

During the weekly proposal review meetings, attended by most of the staff, I could see how these experimental designs came into being. Systematically, the conditions that made up experiments were built around comparisons between tasks and control states. The various conditions were evoked in subjects, as tasks were performed in the course of scanning sessions, repeated and combined with other tasks. There were a number of variations on a basic principle: to contrast the various activations, so as to be able to link a particular function with one or more areas of the brain visibly active on the scans. Sets of comparisons would be organised so as to offer more precisely contrasting pairs of tasks. Confounding elements would be pared down as much as possible, then further controlled by the inclusion of other conditions. See Figure 1 for an example of such contrasting conditions.

In these meetings, I could observe negotiations about what constituted a function to be investigated. It seemed that discussing attention was less problematic than discussing consciousness; meaning would be narrowed down to recognition. The arguments used in these discussions were sometimes labelled as technical ("engineering" constraints), for example, the noise produced by the scanner that would be too loud and interfere with "auditory processes". On occasion, ingenious ways of counteracting different effects were suggested in the meetings, a much appreciated skill in the centre. Sometimes the arguments against particular designs were more procedural: scans would last too long and it would be difficult for subjects to remain still. In some way or other, most designs were modified as an outcome of the meetings. In these discussions, arguments were based on the researchers past experiences, the perceived limitations of the technologies, as well as preferences ultimately based on theories of brain function. This last, more cognitive element became more apparent over the course of meetings, and as I became more familiar with the range of positions in the literature about brain functions, and learned about theories of the brain.

Analysis

After a couple of weeks, I moved from the scanner control room to the second floor where the Fellows had their workspace. This area was set up in two main rooms (the "back room" and the "front room", in relation to the street space), with one long continuous desk along the walls as a sort of ‘figure 8’. In this deliberately open plan
space, each fellow was assigned a Mac computer, and a number of SUN workstations were available for use as people needed to work with large (raw) datasets. These workstations, able to support image-analysis applications, were noticeably and constantly covered with finger-prints. This was especially striking given the level of cleanliness and high standards of housekeeping that reigned at the lab (having a messy desk was the only behaviour for which I was ever openly reprimanded.) These fingerprints were immediately a sign to me that there was more to the images in brain mapping work than what had been allowed for in my interviews. At that point, I felt strongly that I should pursue this imaging theme. While I couldn’t quite put my finger on it at the time, the soiled screens indicated to me a role for the images that wasn’t quite the perceptual aid that my informants had been willing to discuss. Thinking back on this, I now see that these fingerprints pointed to a use of images, an “utilisation”, which in French relates to “outil”, tool. They were doing something with these images, not simply using them to best feed data to their brain via their eyes, according to the cognitive explanations I had been given.

By this time, I had also begun to hear the term “pretty pictures” used (more or less pejoratively), to describe functional imaging. The following is a reconstruction of an exchange between myself and a young psychology postgraduate student who was helping out in the scanner room during an experiment.

(walked in front scanner control room to scanner room to PG standing by neuroscan, introduced myself)
AB: ...I haven’t seen you here before.
PG: I’m doing a PhD in psychology, with X. And I’m going to be making some pretty pictures too so I came down here to see how it goes, and I’m helping out too.
AB: Well, they wouldn’t want you to call them that!
PG: Oh, no no, I mean, I’m not saying that negatively at all. I mean, I use the results.

The phrase would come up again and again, usually to summarise a particular kind of objection to imaging. At around this time, I described some of my attempts to understand the various notions of imaging in the field in a letter to my supervisor:

I wrote to you last time about the difficulty in addressing the question of images. I’m beginning to see what shape the relation to images and other visual proofs takes for these functional imagers (partly from having heard presentations here from other neuroscientists, who don’t have nearly so many qualms about the dynamic of image=result). It partly has to do (or is to do as the Brits say) with the directness of the images, their immediate aesthetic appeal, and the need to have a claim to expertise in understanding them. There is also a major part of disciplinary immaturity that is feeding this, I think. Anyway, I’m glad I’ve kept digging at this one in spite of the lack of ‘data’ at first and the dismissiveness of many of my early informants. And the more it goes, the more I am reminded of my undergraduate
work on religious iconography and iconoclasm. Of course, it's not the image that's being worshipped, and everybody knows that (which is where the Pettologists demand I stop), but that doesn't mean that the particular choice of aid to worship in this way doesn't need explaining. (February 6, 1997, about one third into the first period of fieldwork).

**Mapping**

As I have mentioned, the work pursued at this lab was part of a stream of research that could be labelled brain mapping, where an attempt is made to link various human activities to the performance of functions in the brain that can be localised. Linking reading and areas of activity in the brain requires a number of reductions, or translations of messy everyday human behaviours into streamlined, reproducible tasks for subjects to perform in the scanner. Different centres display different levels of bravura in doing this. Some bank on the possibility of seeing the brain function at a systems level and correlate what are considered to be complex functions with brain maps, for example, intelligence. Others try to build up their research by linking their work either to established cognitive psychology concepts, or to elicit the function of a particular area, starting from an anatomical view of the brain and its connections.

The debates I observed and explanations my presence elicited were precious indications of the parameters used in the formation of the two concepts used in the localisation of function: the where and what, anatomy and function. These two terms are multi-layered, however, and what constitutes a function is debatable as I have noted above, but also highly linked to the disciplinary context in which it is discussed (neurophysiology vs. psychology, for ex).

Most conflictual were the interventions of a neurophysiologist, who would regularly challenge the anatomical knowledge of the researchers, demanding more sophistication in knowledge about the brain's anatomy, more awareness of studies that had been done in animals and provided anatomical guides for some functions. Similar whistle-blowing had also occurred at the Brain Mapping Conference. Finding ways to name these contrasting versions and developing the ability to assign their provenance with some measure of confidence took a number of months. It was largely the result of my own growing competence in neuroscience and the analysis of the written documents (drafts for articles, etc), but also the possibility of contrasting two settings.

Besides having my hunch about imaging revived, during my time in the Fellows' Rooms I also learned a lot about performing analysis on data using the locally developed package of statistical tests to determine the relative activation detectable from the scans. The centre was proud of having provided this tool to the community and insisted on the clarity and efficiency it had brought about: results from different labs could be compared, and these methodological improvements had made imaging more accessible to other neuroscientists.
Interviews with senior researchers later confirmed the importance that the analysis programmes had in the field. Before these analysis programmes existed, one of my informants told me, they “used to just look at these things visually.” Another insisted that these were crucial: he would have “no truck with people who look at images and interpret them.”20 A practice that was arising in some clinical settings. In discussing the maps produced in the lab, the themes of my fieldwork were coming together: what constitutes a function, how is it to be measured, how was the hardness of a measurement to be evaluated, what is the referent of imaging, how is this work scientific and not simply the making of “pretty pictures”—how is a new view of the brain becoming meaningful.

A second lab

Gaining access to this second lab was particularly easy, probably largely due to the fact that I had already done some fieldwork in a leading institution, with some ties to this second site—I had entered the network. When it became possible to do further fieldwork, I could postulate a number of “sensitising differences”. The institutional settings were interesting points of comparison, since if the first lab had been a new centre built up from the ground, with the brain imaging team and methods springing out fully formed, the second setting had been a pioneer in the development of PET, with a tradition of brain mapping extending back for many decades. This centre too had multiple ties to hospital, and university departments, but these were much more long-standing and symbiotic. For example, funding for the scanner depended on investigator-initiated projects and grants, and the junior researchers identified themselves primarily as PhD students attached to particular departments and using the centre, rather than being part of it.

In terms of infrastructures, the contrast was also great. The brain imaging unit was cramped, located on two basement floors in a wing of a teaching hospital and research institute. It was definitely a very different kind of place. When I asked to be introduced to the lab members at a meeting, the director suggested that I send around an email instead. Upon consulting the sys op about a general address for all users, he suggested I send a “broadcast” (a message that appears on the screen as you log on), since the user list was not up to date and members did not read emails addressed to ALL. This drove home the loose boundaries of this lab, striking in comparison to the badge-access double doors of the first lab.

Here too, upon beginning fieldwork, I looked for an area of least discomfort, where I could get used to being in the lab and where people could get used to me. The scanner control room was not as promising a place: it was much more rarely in use, and consisted of a tiny hall-like space not isolated for sound (so that one could only whisper during the scans, so as not to interfere with the cognitive tasks given to subjects.) The place I chose to occupy was behind one of the workstations, calling up the demos and

20 See chapter 4, page 107.
teaching materials of the lab. Behind a console was indeed the most obvious place of work in the imaging unit.

Other contrasts became evident from my efforts to repeat the strategies that had been successful in my previous fieldwork. Upon asking for a tour of the lab, I was told there was nothing to see, that I should just check out the web page to get an idea of the work going on. A different program for analysing data was also being used in this lab. I found different preferences for the coupling of technologies, PET and MRI, (providing functional and anatomical information respectively). The unit was linked to a large cyclotron unit, able to produce a range of radioactive tracers besides O15, so that there were many types of research being pursued besides activation studies. A number of the scans performed were for clinical purposes, these usually assigned to specific days of the week, when clinically-relevant tracers would be produced by the cyclotron. There was therefore a much larger contingent of clinicians and patients in the lab, a fact that perhaps reinforced the feel that the brain imaging facilities were to provide a service (like other departments of the hospital), rather than foremost constitute a research lab.

While the two labs had much in common, the kinds of maps they produce constitute significant variations on the principle of functional anatomy. Each of the two terms is far from being monolithic in brain mapping as I mentioned above. For example, when representing anatomy, brain maps can refer to stereotaxic brain space (x,y,z coordinates representing numbers of mm from a given point of reference) or else to anatomical areas (visual cortex, Broca’s area). The two labs contrasted in their emphasis: The first was more concerned with the statistical validation of measurements of function and the study of functional systems, while the second was more focused on achieving anatomical sophistication and on developing tools for the automated comparison (and eventually evaluation) of anatomical or functional differences in a large number of scans. These particular skills had led to (and been further developed in the course of) a partnership with the private sector, in a complex arrangement between a scanner company, the brain imaging centre and pharmaceutical companies. As far as I could gather, the various partners benefited from the arrangement in the following manner: the lab obtained better scanning technology and contracts, the scanner company could see expertise developed and receive feedback about its scanner technology, while the pharmaceutical company could use the centre’s expertise in image analysis to run a significant part of its clinical trials which required imaging data.30

In the past few pages, I have tried to recount how I came to feel that imaging, making the brain visible, far from being a secondary feature of little interest was on the contrary a very central and complex notion in brain mapping research. In this community

30 This and other arrangements between pharmaceutical companies are ripe for further analysis, form the view of the ‘triple helix’ configuration (Leydesdorff and Eilzerowitz. 1998) but also in terms of how new modes of management of scientific data are being influenced by the ‘auditing’ culture of clinical trials. This issue is briefly evoked in the discussion of atlases in chapter 5.
of neuroscientists, the visual representations produced are quantitative, the maps are made of statistically significant functions and mathematised anatomy, obtained through digital technologies. The visual representations produced flourish in the practices and symbolic systems of brain mappers, as they constitute their disciplinary identity, their object of study, their links to various technologies, the large-scale projects in which they are involved and ultimately, in constituting how the knowledge claims they build find their way into the clinic. This thesis therefore fleshes out the metaphor of a new view of the brain, by analysing the representations produced in brain mapping along a number of dimensions: technological, methodological, institutional and disciplinary, and medical-social.
The Space inside the Skull:
Digital Representations, Brain Mapping and Cognitive Neuroscience
in the Decade of the Brain

Summary

The last two decades have seen a resurgence of interest in exploring the space inside the skull in relation to human activities such as reading, reasoning, or remembering. This new stream of research, often labelled 'cognitive neuroscience', relies to a great extent on techniques of brain mapping, which link functions (these human activities) and anatomy (the space of the brain). Brain mapping is in turn deeply reliant on technologies of brain scanning, such as MRI and PET, to produce and relate measurements of function and anatomy.

Within this research, which ends up linking human mental activity and the hardware of the brain, two important processes are at play: biologisation and digitalisation. The 'mind' is in the course of being 'biologised', as physical substrates for thought and emotion are being localised in various brain areas, and conceptualised as the functions of brain-based networks. Second, this approach is highly embedded in the use of digital technologies, and relies on the creation of a digital context in which measurements of function and of anatomy can be compared. The development of these digital resources in the study of the mind and brain is especially supported by the Human Brain Project, an on-going US-based project, which arose with the Decade of the Brain (the 1990s).

My research addresses the complex new social and technological arrangements in scientific culture that subtend these process of biologisation and digitalisation, based on fieldwork in two leading research centres in Britain and Canada, and through an analysis of the professional literature. Although the focus is on research settings, this dissertation is written with an awareness that brain mapping reshapes our definitions of mind and brain, and that this has significant consequences for concepts of the physical and the mental. The institutions in which these concepts find their articulation are also affected—the legal system where responsibility for one's actions depends on mental state; medical practices of diagnosis and screening, as well as patterns of care; social provisions for the mentally ill; and strategies for education and child care. Where possible, these social consequences are signalled.

* 

Science and technology studies have amply shown that new knowledge only becomes recognised as meaningful once a context for its use has been developed. Other scholarship in this area has shown how the production of traces, and their circulation, are key components of scientific work. A focus on representations, which guides this dissertation, enables me to address both themes: representations are only meaningful once there is
agreement on their production and interpretation, and the circulation of representations of
the mind and brain give insight into the deployment of this new stream of research. What
started out as an illustrative metaphor for this project, “a new view of the brain” has
turned out to be at the core of my analysis of this growing stream of research.

These insights from science and technology studies led me to ask the following questions:
How are scans read? What does a map of the brain show? How do atlases of the brain
become authoritative? Each chapter traces how a specific type of representation has
developed. These include: the application of brain imaging technologies (scans) to new
phenomena that bridge the disciplines of mind and brain, new concepts of the brain’s
function and the development of new experimental paradigms (maps), the constitution of
a new research community whose members share an empirical style (imagers), and
finally, the intersection of brain mapping and the Human Brain Project, where a new
digital kind of immutable mobile arises (atlases). Each chapter therefore addresses
increasingly complex instances of the creation, manipulation and circulation of
representations.

**

The first chapter sets out the importance of representations in the field of brain mapping.
It also contains a discussion of how representations are to be studied, and of the features
relevant to their analysis. The relation of representations to digitalisation and
biologisation are also explored. Chapter 2 considers the colourful scans used in this
research. Here, scans are examined as representations that have had different meanings,
depending on the uses to which they have been put. I trace the changing definitions of
what these scans show, contrasting early use in neurological settings and later use in
psychological experiments. The different ways in which researchers ‘make sense’ of the
information provided by scans are examined in terms of the type of questions asked
(diagnostic-clinical v. research), the way scans are understood (visually examined v.
quantitatively analysed), and the way activity detected by scanners is reconciled with the
anatomy of the brain. The development of the Talairach conventions features prominently
in this chapter, since they come to constitute the digital context in which function and
anatomy can be related, ultimately providing a way to show the mind-in-the-brain.

Maps are the focus of Chapter 3. Functional imaging claims to investigate the highest
human functions, in the whole, intact brain, in vivo, and to represent these functions in
the shape of maps. This chapter addresses first of all how experiments are designed to
contrast functions in human brains and produce these maps. It also examines how these
experiments, and the evidence they produce (functions mapped unto the brain), differ
from other approaches in cognitive and neural science. The range of functions that are
mapped is also considered, with special emphasis on how cultural and social influences
on the mind come to be inscribed onto maps of the brain. I argue that the project of
mapping the brain is best understood when not solely regarded as ‘reductionist’, but also
as being productive of new relations. By inscribing the mind into the brain, the ‘mind’ can
circulate in the areas where the body is considered, namely biomedical institutions.
The ways in which brain mapping contrasts with other approaches to the mind and brain is further investigated in Chapter 4, by focusing on the way representations used in brain mapping constitute a particular empirics, a way of knowing that is specific to this group of researchers. Brain mappers both love and reject the images they use. This paradoxical relationship is the result of the rejection of some aspects of representations (the visual appeal, for example, which is seductive and therefore not rational), and the simultaneous reliance on other aspects (for example, the use of representations to convey spatiality).

The manner in which brain mappers discuss the representations they use is analysed in relation to the claims they make for the unique insights provided by brain mapping. By identifying the elements that are embraced and rejected in the use of representations, a specific digital esthetic is shown to be arising in the context of functional imaging, and the boundaries of the community can be traced according to this shared understanding of images.

Atlases of the brain are the final representations to be analysed. While their development originates in the brain mapping community, as an answer to the need for a baseline to interpret activations, the Human Brain Project has fostered the expansion of these atlases. This chapter traces the background to the HBP's explicit goal: the development of neuroinformatics in order to integrate the various subdisciplines of neuroscience through a number of digital resources. These atlases are analysed in terms of their dual role as new authoritative representations of normality and disease, as well as repositories of many types of knowledge about the brain (different levels of anatomy, of functional and metabolic information, etc). Both functions (evaluating scans from different subjects, and comparing different types of data about the brain) are shaped by the possibility of automatically manipulating and accumulating large numbers of scans, through the development of standard spaces for handling digital information. The impact of these new atlases on concepts of objectivity, normativity and scientific progress is also analysed in this chapter.

The final chapter reviews the main findings, regarding the way functional imaging moves scientific work with scans of the body away from an optical understanding and towards a digital mode of knowing. The implications of the new ideals of quantitation and automation (core elements of this digitality) are also discussed, especially in terms of their consequences for the biological. Degrees of variability, probability of normality, and averaged diseased brains become so many new concepts in the evaluation of health and illness as measurable sets of factors. The challenges to clinical traditions posed by these changes are also noted. Finally, this chapter considers brain mapping and the HBP in relation to other contemporary projects, which also involve biologisation and digitalisation (the Human Genome Project, the Cochrane Initiative, the Visible Human Project), in order to reflect on the particularities of the endeavour to explore the mind-in-the-brain and the general trend towards the use of digital tools in science.

***
De ruimte binnen de schedel:
Digitale representaties, hersencartografie en cognitieve neurowetenschap in het Decennium van het Brein.

Samenvatting

De laatste twee decennia hebben een opleving laten zien van de interesse in het exploreren van de ruimte binnen de schedel in relatie tot menselijke activiteiten als lezen, redeneren en herinneren. Dit nieuwe onderzoeksgebied, dikwijls ‘cognitieve neurowetenschap’ genoemd, steunt in grote mate op technieken van hersencartografie, die functies (de menselijke activiteiten) verbinden met anatoom (de ruimte van de hersenen).

In dit onderzoek, dat leidt tot het verbinden van de geestelijke activiteiten van mensen met de hardware van het brein, spelen twee belangrijke processen: biologiseren en digitaliseren. De ‘geest’ wordt ‘verbiologiseerd’ door de lichamelijke substraten van cognitie en emotie te localiseren in verschillende hersengebieden, en ze te conceptualiseren als de functies van netwerken in het brein. Deze benadering is, ten tweede, diep ingebakken in het gebruik van digitale technologie, en ze vereist het creëren van een digitale context waarin metingen van functie en anatomie kunnen worden vergeleken. De ontwikkeling van zulke digitale hulpmiddelen in het onderzoek van geest en hersenen wordt vooral ondersteund door het Human Brain Project, een Amerikaans initiatief uit het Decennium van het brein (de jaren negentig).

Mijn onderzoek is gericht op de complexe nieuwe sociale en technologische ordeningen in de wetenschappelijke cultuur die deze processen van biologiseren en digitaliseren schragen. Het is gebaseerd op veldwerk in twee vooraanstaande onderzoekscentra in Groot Brittannië en Canada, en op een analyse van de wetenschappelijke literatuur. Hoewel het onderzoek centraal staat, is dit proefschrift geschreven in het bewustzijn dat hersencartografie onze definities van geest en hersenen verandert, en dat dit belangrijke consequenties heeft voor de begrippen lichaam en geest. Ook de instituties waarin deze begrippen worden gearticuleerd worden beïnvloed – het juridische systeem, waar toerekeningsvatbaarheid afhankt van geestesgesteldheid; medische praktijken van diagnose en screening, alsmede zorgpatronen; en strategieën voor onderwijs en opvoeding. Waar mogelijk wordt op deze sociale consequenties gewezen.

Wetenschaps- en technologiestudies hebben overvloedig aangetoond dat de betekenis van nieuwe kennis pas wordt herkend wanneer een context voor het gebruik ervan is ontwikkeld. Ander onderzoek op dit gebied heeft laten zien hoe de productie van sporen, en hun circulatie, essentiële componenten zijn van wetenschappelijk werk. Door representaties centraal te stellen, het leidende principe in dit proefschrift, kan ik beide thema’s behandelen: representaties zijn pas betekenisvol als er overeenstemming is over
hun productie en interpretatie, en de circulatie van representaties biedt inzicht in de
toepassing van dit nieuwe type onderzoek. Wat begon als een verhelderende metafoor
voor dit project, ‘een nieuwe blik op het brein’, is de kern geworden van mijn analyse van
dit groeiende onderzoeksgebied.

Deze inzichten uit het wetenschaps- en technologieonderzoek brengen mij tot de
volgende vragen: hoe worden scans gelezen? Wat laat een kaart van de hersenen zien?
Hoe verkrijgen hersenatlassen autoriteit? Elk hoofdstuk gaat de ontwikkeling van een
bepaald type representatie. Hiertoe behoren: de toepassing van ‘brain imaging’ technieken
op nieuwe verschijnselen die de disciplines van geest en hersenen overbruggen; nieuwe
concepten van het functioneren van de hersenen, en het ontwikkelen van nieuwe
experimentele paradigma’s; de vorming van een nieuwe onderzoeksgerelateerd
waarvan de leden een empirische stijl delen (‘imagers’); en ten slotte het snijpunt van
hersencartografie en het Human Brain Project, waar een nieuw, digitaal soort ‘immutable
mobile’ ontstaat (atlassen). Elk hoofdstuk behandelt dus steeds complexer wordende
gevallen van de creatie, manipulatie en circulatie van representaties.

Het eerste hoofdstuk zet het belang uiteen van representaties op het gebied van
hersencartografie. Het bevat tevens een discussie van de vraag hoe representaties moeten
worden bestudeerd, en welke kenmerken relevant zijn voor de analyse. De relaties tussen
representaties enerzijds en digitalisering en biologisering anderzijds worden ook
onderzocht. Hoofdstuk 2 beschouwt de kleurrijke scans die in dit onderzoek worden
gebruikt. Hier worden scans onderzocht als representaties die een verschillende betekenis
krijgen, al naar gelang het gebruik dat ervan wordt gemaakt. Ik ga de veranderende
definities na van wat deze scans tonen, en contrastteer de vroege toepassing in de
neurologie en het latere gebruik in psychologische experimenten. De diverse manieren
waarop onderzoekers ‘wijzen’ uit de informatie die de scans bieden worden
onderzocht in termen van het soort vragen dat wordt gesteld (klinisch-diagnostisch
tegenover wetenschappelijk), de wijze waarop scans worden begrepen (visueel
onderzocht tegenover kwantitatief geanalyseerd), en de manier waarop de activiteit die de
scanners detecteren in overeenstemming wordt gebracht met de anatomie van de
hersenen. De ontwikkeling van de Talairach conventies speelt een belangrijke rol in dit
hoofdstuk, aaneengesloten bij de digitale context gaan vormen waarin functie en anatomie aan
elkaar kunnen worden gerelateerd, en uiteindelijk een manier bieden om de geest-in-het-
brein te laten zien.

Kaarten staan centraal in hoofdstuk 3. ‘Functional imaging’ beweert de hoogste
menselijke functies te bestuderen, in het gehele, intacte brein, in vivo, en deze functies te
representeren in de vorm van digitale kaarten. Dit hoofdstuk behandelt ten eerste hoe
experimenten worden opgezet om functies in menselijke hersenen te contrasteren en deze
kaarten te produceren. Het onderzocht tevens hoe deze experimenten, en de resultaten die
ze opleveren (functies afgebeeld op de hersenen) verschillen van andere benaderingen in
de cognitieve en neurologische wetenschappen. De verscheidenheid aan functies die
worden afgebeeld wordt ook beschouwd, met speciale aandacht voor de wijze waarop culturele en sociale invloeden op de geest worden ingeschreven in kaarten van de hersenen. Ik beargumenteer dat het project van het in kaart brengen van de hersenen het best kan worden begrepen als niet slechts ‘reductieïstisch’, maar ook als een bron van nieuwe relaties. Door de geest in te schrijven in het brein, kan de ‘geest’ circuleren in gebieden waar het lichaam wordt beschouwd, biomedische instituties namelijk.

De contrasten tussen hersencartografie en andere benaderingen van geest en brein worden verder onderzocht in hoofdstuk 4. Hierin staat centraal de manier waarop de representaties die worden gebruikt in hersencartografie een bepaalde empirie constitueren, een voor een bepaalde groep onderzoekers specifieke wijze van kennen. Hersencartografen hebben een haat-liefdeverhouding met de beelden die ze gebruiken. Deze paradoxale relatie is het gevolg van het verwerpen van bepaalde aspecten van representaties (hun visuele aantrekkelijkheid bijvoorbeeld, die verleidelijk en daarom niet rationeel is), terwijl men tegelijkertijd vertrouwt op andere aspecten (bijvoorbeeld het gebruik van representaties om ruimtelijkheid over te brengen). De wijze waarop hersencartografen de representaties die ze gebruiken, bespreken, wordt geanalyseerd in relatie tot de aanspraak die ze maken op unieke inzichten uit hersencartografie. Door na te gaan welke elementen worden aanvaard dan wel verworpen, wordt duidelijk dat in de context van ‘functional imaging’ een bepaalde digitale esthetiek ontstaat: de grenzen van de gemeenschap worden bepaald door dit gedeelde begrip van beelden.

Hersenatlassen zijn de laatste representaties die worden geanalyseerd. Hun ontwikkeling begon in de gemeenschap van hersencartografen, als een antwoord op de behoefte aan een baseline om activaties te interpreteren, maar het Human Brain Project heeft een uitbreiding van deze atlassen gestimuleerd. Dit hoofdstuk traceert de achtergrond van het expliciete doel van het HBP: de ontwikkeling van neuroinformatica om de verschillende subdisciplines van de neurowetenschap te integreren door middel van een aantal digitale hulpmiddelen. Deze atlassen worden geanalyseerd in termen van hun dubbele rol als nieuwe gezaghebbende representaties van normaliteit en ziekte, en als opslagplaatsen van vele soorten kennis over de hersenen (verschillende niveaus van anatomie, van functionele en metabolische informatie, enzovoort). Beide functies (het evalueren van scans van verschillende proefpersonen, en het vergelijken van verschillende soorten data m.b.t. de hersenen) worden gevormd door de mogelijkheid automatisch grote aantallen scans te vergelijken en vergaren, door middel van de ontwikkeling van standaarden voor het manipuleren van scans en van standaardruimtes om digitale informatie in te plaatsen. De invloed van deze nieuwe atlassen op de begrippen objectiviteit, normativiteit en wetenschappelijke vooruitgang wordt eveneens geanalyseerd in dit hoofdstuk.

Het laatste hoofdstuk geeft een overzicht van de belangrijkste resultaten en beschouwt hoe ‘functional imaging’ het wetenschappelijke werk met scans van het lichaam van een optisch begrip naar een digitale wijze van kennen heeft gedreven. Ook de implicaties van de nieuwe idealen van kwantificering en automatisering (kernelementen van deze digitaliteit) worden behandeld, vooral met betrekking tot het biologische domein. Graden van variabiliteit, de waarschijnlijkheid van normaliteit, en gemiddelde zieke hersenen zijn
zowel nieuwe concepten in het evalueren van gezondheid en ziekte als meetbare verzamelingen van factoren. De uitdaging waarvoor klinische tradities worden gesteld door deze veranderingen wordt eveneens besproken. Dit hoofdstuk beschouwt ten slotte hersencartografie en het HBP in relatie tot andere hedendaagse projecten die biologisering en digitalisering met zich meebrengen (het Human Genome Project, het Cochrane Initiatief, het Visible Human Project), om zodoende te reflecteren op de bijzonderheden van het exploreren van de geest-in-het-brein en de algemene trend naar het gebruik van digitale instrumenten in de wetenschap.

***

200
Works Cited

Abbot, Allison

Ackerman, Sandra

Aine, Cheryl

Alpers, Svetlana

Amsterdamska, Olga and Anja Hiddinga

Amsterdamska, Olga

Andreassen, Nancy

Andreassen, Nancy, Gregg Cohen, Greg Harris, Ted Cizzato, Jussi Pakinnen, Karim Rezai, Victor Swayze

Andreassen, Nancy N. Stephen Arndt, Victor Swayze II, Ted Cizzato, Michael Flaim, Daniel O’Leary, James C Erhardt, William T.C. Yuh

Anguelov, Zlatko

Atkins, Daniel

Atkinson, Paul

Barinaga, Marcia

Barinaga, Marcia
Bastide, Françoise

Beaulieu, Anne

Begley, Sharon

Berg, Marc

Blakemore, MJ and JB Harley

Bloom, Floyd F.


Bower, James,

Blume, Stuart

Brinkley, James, Lloyd Myers, Jeff Prothero, Greg Heil, Jay Tsuruda, Kenneth Maravilla, George Ojemann and Cornelius Rosse

Brtter, John T.

Buechel, Christian, Jennie Coulil and Karl Friston

Butler, Judith

Buschbaum, Monte

Cabeza, Roberto and Lars Nyberg

Canguilhem, George (translated by Carolyn Fawcett)

Carson, Richard

Cartwright, Lisa

Cartwright, Lisa

Cartwright, Lisa

Cartwright, Lisa, and Brian Goldfarb

Castel, Robert

Cheng, Kang, Hideaka Fujita, Iwao Kanno, Suichi Miura and Keiji Tanaka

Cherniak, Christopher

Chugani, Harry, Michael Phelps, and John Mazziotta

Chugani, Harry
Clark, Campbell  
Journal of Cerebral Blood Flow and Metabolism. Supplement. 7: S113-16.

Clifford, James and George F. Marcus  

Clifford, James  

Cohen, Jonathan  

Colbert, Charles  

Coleman, R. Edward  

Cotterill, Rodney  

Cox, Jerome  

Crary, Jonathan  

Crary, Jonathan and Sanford Kwinter  

Crease, R.  

Crick, Francis and Edward Jones  

Damasio, Hannah, Thomas Grabowski, Daniel Tranel, Richard Ithicwa, and Antonio Damasio  

Daston, Lorraine  

Daston, Lorraine and Peter Galison  

Davis, Audrey

Dehue, Trudy

Dennet, Daniel

Derksen, Maarten

Derksen, Maarten

Desrosieres, Alain

van Dijck, Jose

van Dijck, Jose

DiChiro, G. and RA Brooks

Draaisma, Douwe

Drevets, WC, TO Video, AK Macleod, JW Heller, and ME Raichle

Drury, Heather and David Van Essen

Duara, R. I. Barker, and C. Luis

Dumit, Joseph

205
Dumit, Joseph

Dumit, Joseph

Edgerton, Samuel

Eisenstein, E.

Engels, Jerome

Enserink, Martin

van Essen, David and Heather Drury

Evans, Alan, C. Beil, S. Marrett, C. Thompson, A. Hakim.

Evans, Alan, Sean Marrett, Terry Peters.

Evans, Alan, Sean Marret, J. Torrescurso, S. Ku and Louis Collins

Evans, Alan, Sean Marret, Peter Neelin, Louis Collins, Keith Worsley, Weiqian Dai, Sylvain Millot, Ernst Meyer, Daniel Bub

Faas, Erik

Farah, Martha


Fox, Peter, Joel Perlmutter and Marcus Raichle

Fox, Peter, Joel Perlmutter and Marcus Raichle

Fox, Peter and Marty Woldorff

Frackowiak, Richard

Frackowiak, Richard

Frackowiak, Richard

Frackowiak, Richard, Karl Friston, Chris Frith, Ray Dolan, John Mazziotta

Frick, Mathis, Naresh Gupta, John Sunderland, Michael Best, Joseph Rysavy, Chyng-Yann Shiue

Friston, Karl

Friston, Karl

Friston, Karl, Richard Passingham, J Nutt, John Heather, Guy Sawle and Richard Frackowiak

Friston, Karl, Christopher Frith, Paul Liddle, Ray Dolan, Adriaan Lammerstma and Richard Frackowiak

Friston, Karl, Christopher Frith, Paul Liddle, Richard Frackowiak

Frith, Christopher, Karl Friston, Paul Liddle, Richard Frackowiak

Frith, Chris, and Raymond Dolan
Fujimura, Joan and Michael Fortun

Galaburda, Albert, Marjorie Leay, Tomas Kemper and Norman Geschwind, Norman

Galison, Peter

Gazzaniga, Michael

Gershon, Diane

Gershon, Diane

Gevins, Alan, Brian Cutillo, Don DuRousseau, Jian Le, Harrison Leong, Nancy Martin, Michael E Smith, Steven Bressler, Paul Brickett, Judith McLaughlin, Nicholas Barbaro and Kenneth Laxer

Gibbons, Ann

Gilman, Sid

Gilman, Sid

Gloor, Pierre

Goertzel, Ben

Gooding, David

Goodwin, Charles

Goodwin, Charles

Gopnik, Alison, Andrew Melzoff and Patricia Kuhl

209
Gould, Stephen Jay  

Gregory, Jane and Steve Miller  

Greitz, T., M. Bergstroem M. J. Boethius, D. Kingsley, T. Ribbe  


Grillner, S.  

Hacking, Ian  

Hacking, Ian  

Hacking, Ian  

Hall, Stephen  

Hammersley, Martyn and Paul Atkinson  

Haraway, Donna  

Harrington, Anne  

Harrington, Anne  

Harvey, Paul and John Krebs  

Haxby, James  

Haxby, James, Cheryl Grady, Leslie Ungerleider and Barry Horwitz  
210

Heath, Deborah

Henderson, Kathryn

Hiddinga, Anja

Hoffman, JM. M. Hanson, R. Coleman

Horn, David

Huerta, Michael, Stephen H. Koslow and Alan Lesnner

Huerta, Michael and Stephen Koslow

Huerta, Michael, Line Mathiessen, Per Roland and Arthur Toga

Hugdahl, Kenneth

ICB M [John Mazziotta, Arthur Toga, Alan Evans, Peter Fox. Jack Lancaster]

ICBM

Iovine, Vicki

Jacobs, Gwen

Jones, Terry

211

Jouandet, Marc, Mark Tramo, Daniel Herron, Allison Hermann, William Loftus, Josh Bazell and Michael Gazzaniga

Judd, Lewis

van Kammen, Jessika

Kandel, Eric

Kanno, Iwao, Hideaka Fujita, and Suichi Miura

Karp, Joel and Richard Freifelder

Kennedy, Charles

Kember, Sarah

Kember, Sarah

Kevles, Bettyann

Klein, Denise, Brenda Milner, Robert Zatorre, Ernst Meyer, Alan Evans
Knorr-Cetina, Karen  

Knorr-Cetina, Karen  

Knorr-Cetina, Karin  

Koshland, Daniel  

Kosslyn, Stephen  

Kosslyn, Stephen  

Kosslyn, Stephen, Nathaniel Alpert, William Thompson, Vera Malijkovic, Steven Weise, Christopher Chabris, Sanya Hamilton, Scott Rauch and Ferdinando Buonannoti  

Kosslyn, Stephen and Oliver Koenig  

Koslow, Stephen, et al editors  

Koslow, Stephen and Michael Huerta  

Kulynych, Jennifer  

Lancaster Jack, Peter Fox, Gwendolyn Davis, Shawn Mikiten  

Latour, Bruno  

Latour, Bruno  

213
Latour, Bruno and Steve Woolgar  

Law, John and John Whittaker  

Lawrence, Susan and Kate Bendixen  

Leydesdorff, Loet and Henry Etzkowitz  

Lippman, Abby  

Lock, Margaret  

Loewy, Iliana  

Lumsdon, Kevin  

Lynch, Michael  

Lynch, Michael  

Lynch, Michael  

Lynch, Michael  

Lynch, Michael and Steve Woolgar  

Magistretti, Pierre, Luc Pellerin, Douglas Rothman and Robert Shulman  
Martin, Emily  
1991 The Egg and the Sperm: How science has Constructed a Romance Based on Stereotypical Male-female Roles. Signs 16(3): 485-501

Martin, Emily  

Matthesen, Line  

Mazziotta, John  

Mazziotta, John, Michael Phelps, Joann Miller, David Kuhl  

Mazziotta, John, Michael Phelps, David Kuhl, Marc Nuwer, James Packwood, Jeffrey Metter, Jerome Engel  

Mazziotta, John, Michael Phelps, Richard Carson, David Kuhl  

Mazziotta, John and Jerome Engel  

Mazziotta, John and Stephen Koslow  

Mazziotta, John, Charles Pelizzari, George Chen, Fred Bookstein and Daniel Valentino  

Mazziotta, John, Arthur Toga, Alan Evans, Peter Fox, Jack Lancaster  

Mazziotta, John C. Arthur W. Toga, Alan Evans, Peter Fox and Jack Lancaster  

McGrane, Bernard

Mehler, Jacques, John Morton and Peter Jusczyk

Metter EJ, CG Wasierlai, D Kuhl, WR Hanson, MF Phelps

Minoshima, Satoshi, Robert Koepppe, Kirk Frey, Makiko Ishihara, David Kuhl

Mitchell, William

Mountcastle, Vernon

Motlik Alison.

Mulder, G., A. Wijers, J. Lange, B. Buijink, L. Mulder, A. Willemsen, A. Paans

National Science Foundation

National Institute of Health

National Institute of Health

Nelkin, Dorothy and Tancredi, Laurence

NIWI

O’Connell, Joseph

O’Mara, Shane
Paller, Ken
1995 If a picture is worth a thousand words, how many pictures is a word worth? [Peer Commentary on Précis of Images of Mind]. Behavioral and Brain Sciences 18: 327-383.

Pandolfi, F.

Pasveer, Bernike

Pasveer, Bernike

Paus, Tomas, Alex Zijdenbos, Keith Worsley, Louis Collins, Jonathan Blumenthal, Jay Giedd, Judith Rapoport, Alan Evans

Pechura, Constance and Joseph Martin

Penfield, Wilder and Theodore Rasmussen
1950 The Cerebral Cortex of Man; a Clinical Study of Localization of Function. New York: Macmillan.

Petersen, Steven, Peter Fox, Michael Posner, Mark Mintun and Marcus Raichle

Petersen, Steven, Fox, Peter, Raichle, Marcus

Phelps, Michael

Phelps, Michael, John Mazziotto, David Kuhl, Marc Nuweer, James Packwood, Jeffery Mett, Jerome Engel

Pinker, Steven

van der Ploeg, Irma

Poeppel, David and Susan Johnson
Porter, Theodore

Posner, Michael

Posner, Michael

Posner, Michael

Posner, Michael, Steven Petersen, Peter Fox and Marcus Raichle

Posner, Michael and Marcus Raichle

Posner, Michael and Marcus Raichle

Powers, William, Leonard Berg, Joel Perlmutter, Marcus Raichle

Pratt, Mary Louise

Price, Cathy

Prins, Ad

Programme Announcement (PA 96-002)

Purpura, Dominick

Purves, Dale and Leonard White

Pylyshyn, Zenon

Rabinow, Paul

Raichle, Marcus

Raichle, Marcus

Raichle, Marcus

Raichle, Marcus

Raichle, Marcus

Raine, A., J. Meloy, S. Bihrlfe, J. Stoddard, L. LaCasse, M. Busehbaum

Rapoport, Stanley

Rapp, Raiana

Reiman, Eric, Maureen Fusselman, Peter Fox and Marcus Raichle

Rich, Dayton

Ricoeur, Paul, and Changeux, Jean-Pierre

Roberts, Leslie
Roland, Per

Roland, Per

Roland, Per and Lars Friberg

Roland, Per, CJ Graufelds, J Wahlin, L Ingelman, M Agersson, A Ledberg, J Pedersen, S Akerman, A Dabringhaus and K Zilles

Roland, Per and Karl Zilles

Roland, Per and Karl

Roland, Per and Karl Zilles
1996 The Developing Computerized Human Brain Database for All Imaging Modalities. In Neuroimage 4: S39-S47.

Rose, Nikolas

Rose, Nikolas

Rose, Stephen

Rudwick, Martin

Russo, Eugene

Sappol, Michael

Sargent, Pauline

220

Smith, Roger

Solsa, Robert

Stafford, Barbara

Stafford, Barbara

Star, Susan Leigh

Star, Susan Leigh and James Griesemer

Steinmetz and Seitz.

Swanson, Larry

Strother, S, J-S Liow, J. Moeller, J. Stidits, V. Dahwan, D. Rottenberg

Tagg, John

Tagg, John

Tagg, John

Talairach, Jean and Pierre Tournoux
Tancred Laurence, Nora Volkow
1992 A Theory of the Mind/brain Dichotomy with Special Reference to the
Contribution of Positron Emission Tomography. Perspective in Biology and Medicine,
Summer, 35(4): 549-71

Taubes, Gary

Ter-Pogossian, Michel
1992 The Origins of Positron Emission Tomography Seminars in Nuclear Medicine, July,

Ter-Pogossian, Michel, M. Phelps, E. Hoffman
1975 A Positron Transaxial Tomograph for Nuclear Medicine Imaging (PETT). Radiology 114:
89-98.

Terry, J and Urla, J.
1995 Deviant Bodies: Critical Perspectives on Difference in Science and Popular Culture,
Bloomington, Indiana: Indiana University Press.

Thompson, Paul, David McDonald, M. Mega, Colin Holmes, Alan Evans, Arthur Toga

Thompson, Paul, Craig Schwartz, Robert Lin, Robert Aelia Kahn and Arthur Toga
of Neuroscience, July 1, 16(13): 4261-4274.

Toga, Arthur

Toga, Arthur W. and John C. Mazziotta

Toga, Arthur and Paul Thompson
1998 Surface-Based Strategies for High-Dimensional Brain Image Registration. In Brain

Traweek, Sharon
1988 Lifetimes and Beamtimes: The World of High Energy Physics. Cambridge, Massachusetts:
Harvard University Press.

Tuft, Edward
Press.

Tuft Edward

Volavka, J.

Volkow, Nora, and Laurence Tancredi

223

Wagner, Henry

Wagner, Anthony, Daniel Schacter, Michael Rotte, Wilma Koutstall, Anat Maril, Anders Dale, Bruce Rosen, Randy Buckner

Waldby, Catherine

Waldby, Catherine

Ward, Greg

Wingerson, L.

Wolf, Tom

Woods, Roger

Wood, C. C.

Wood, Denis

Young, Robert

Yoxen, Edward

Zilles, Karl, Axel Schleicher, Christian Langemann, Katrin Amunts, Patricia Morosa, Nicola Palomero-Gallagher, Thorsten Schormann, Harmut Mohlberg, Uli Buergel, Helmut Steinmetz, Gottfried Schlaug, and Per Roland