
Contents

Preface xiii

Chapter 1

An Introduction to fMRI 1

What Is fMRI? 3

Measurement versus manipulation techniques 4

Box 1.1 What Is fMRI Used For? 6

Key concept: Contrast 10

Key concept: Resolution 13

History of fMRI 16

Early studies of magnetic resonance 16

NMR in bulk matter: Bloch and Purcell 18

The earliest MR images 19

Box 1.2 A Nobel Prize for MRI 22

Growth of MRI 24

Organization of the Textbook 25

Physical bases of fMRI 26

Principles of BOLD fMRI 26

Design and analysis of fMRI experiments 27

Applications and future directions 28

Summary 29

Suggested Readings 29

Chapter References 30

Chapter 2

MRI Scanners 31

How MRI Scanners Work 31

Static magnetic field 32

Radiofrequency coils 35

Gradient coils 38

Shimming coils 41

Computer hardware and software 41

Experimental control system 43

Physiological monitoring equipment 43

MRI Safety 44

Effects of static magnetic fields on human physiology 44

Box 2.1 Outline of an fMRI Experiment 22

Translation and torsion 50

Gradient magnetic field effects 51

Radiofrequency field effects 52

Claustrophobia 53

Acoustic noise 54

Summary 54

Suggested Readings 55

Chapter References 55

Chapter 3

Basic Principles of MR Signal Generation 57

QUANTITATIVE PATH 59

- Nuclear Spins 59
- Spins in an External Magnetic Field 60
- Magnetization of a Spin System 63
- Excitation of a Spin System and Signal Reception 64
- Relaxation Mechanisms of the MR Signal 66
- Conceptual Summary of MR Signal Generation 67
- CONCEPTUAL PATH 68
- Common Terms and Notations 68
- Nuclear Spins 69
- Magnetic Moment 69
- Angular Momentum 70
- Spins in an External Magnetic Field 71
 - Spin precession 72
- Energy Difference between Parallel and Antiparallel States 74
- Magnetization of a Spin System 76
- Excitation of a Spin System and Signal Reception 78
 - Spin excitation 78
 - Box 3.1 A Quantitative Consideration of the Rotating Reference Frame 80
 - Signal reception 83
- Relaxation Mechanisms of a Spin System 85
- The Bloch Equation for MR Signal Generation 87
- Summary 87
- Suggested Readings 88

Chapter 4

Basic Principles of MR Image Formation 89

CONCEPTUAL PATH 90

- Slice Selection 91

- Frequency Encoding 94
- Phase Encoding 95
- Summary of Image Formation (Conceptual Path) 97
 - Box 4.1 An Example of Spatial Encoding 98
- QUANTITATIVE PATH 100
- Analysis of the MR Signal 100
 - Longitudinal magnetization (M_z) 102
 - Transverse magnetization (M_{xy}) 103
 - The MR signal equation 106
- Slice Selection, Spatial Encoding, and Image Reconstruction 107
 - Slice selection 107
 - Two-dimensional spatial encoding in k -space:
 - Frequency and phase encoding 110
 - Relationship between image space and k -space 114
 - Converting from k -space to image space 117
- 3-D Imaging 118
- Potential Problems in Image Formation 119
- Summary 120
- Suggested Readings 121

Chapter 5

MRI Contrast Mechanisms and Acquisition Techniques 123

- Static Contrasts 124
 - Proton-density contrast 126
 - T_1 contrast 128
 - T_2 contrast 131
 - T_2^* contrast 133
 - Chemical contrast 134
- Motion Contrasts 136
 - MR angiography 136
 - Diffusion-weighted contrast 138
 - Perfusion-weighted contrast 140
 - Box 5.1 Diffusion Tensor Imaging 142
- Image Acquisition Techniques 147
 - Echo-planar imaging 148
 - Spiral imaging 150

- Signal recovery and distortion correction for EPI and spiral images 152
- Parallel imaging 153
- Summary 156
- Suggested Readings 156
- Chapter References 157

Chapter 6

From Neuronal to Hemodynamic Activity 159

- Information Processing in the Central Nervous System 162
 - Neurons 162
 - Glia 163
 - Neuronal membranes and ion channels 164
 - Synapses: Information transmission between neurons 167
 - Synaptic potentials and action potentials 168
- Cerebral Metabolism: Neuronal Energy Consumption 170
 - Adenosine triphosphate (ATP) 171
 - The energy budget of the brain 172
- The Vascular System of the Brain 174
 - Arteries, capillaries, and veins 175
 - Arterial and venous anatomy of the human brain 177
 - Microcirculation 179
- Blood Flow 180
 - Control of blood flow 181
 - Feedback and feedforward control of blood flow 183
 - The neurovascular unit 186
 - Pericytes 187
 - Nitric oxide 189
 - Vascular conducted response 189
 - Box 6.1 Hemodynamic Balance: Push-Pull and Vascular Steal 190
- The Coupling of Blood Flow, Metabolism, and Neuronal Activity 192
 - The oxygen-glucose index (OGI) 192
 - Box 6.2 PET Imaging 193

- Explanations for the uncoupling of CBF, CMR_{O_2} , and CMR_{glu} 195
- Functional hyperemia redux 196
 - Box 6.3 Primer on Neuroanatomy 198
- Summary 206
- Suggested Readings 206
- Chapter References 207

Chapter 7

BOLD fMRI: Origins and Properties 211

- History of BOLD fMRI 212
 - Discovery of BOLD contrast 213
- The Growth of BOLD fMRI 216
 - Contributing factors 216
 - Early fMRI studies 219
 - Box 7.1 Functional Studies Using Contrast Agents 220
- The BOLD Hemodynamic Response 223
 - The initial dip 225
- The Neural Correlates of BOLD Contrast 229
 - Box 7.2 Sustained Negative BOLD Signals 230
- Spatial Resolution 238
 - Spatial specificity in the vascular system 240
 - What spatial resolution is needed? 243
- Temporal Resolution of fMRI 245
 - What temporal resolution is needed? 248
 - Effects of stimulus duration and timing 250
- Linearity of the Hemodynamic Response 255
 - Properties of a linear system 256
 - Evidence for rough linearity 258
 - Challenges to linearity 260
 - fMRI-adaptation 261
- Summary 264
- Suggested Readings 265
- Chapter References 266

Chapter 8

Signal, Noise, and Preprocessing of fMRI Data 271

Understanding Signal and Noise 272

Signal and noise defined 273

Box 8.1 Terminology of fMRI 274

Functional SNR 277

Effects of Field Strength on fMRI Data 278

Field strength and raw SNR 278

Field strength and spatial properties of activation 279

Challenges of high-field fMRI 282

Sources of Noise in fMRI 283

Thermal noise 284

System noise 286

Motion and physiological noise 287

Non-task-related neural variability 290

Behavioral and cognitive variability in task performance 290

Box 8.2 Variability in the Hemodynamic Response over Subjects and Sessions 292

Preprocessing 295

Quality assurance 295

Slice acquisition time correction 297

Head motion: An overview 299

Prevention of head motion 302

Correction of head motion 304

Distortion correction 306

Functional-Structural Coregistration and Normalization 308

Functional-structural coregistration 309

Spatial normalization 310

Temporal and Spatial Filtering 313

Temporal filtering 314

Spatial filtering 315

Summary 318

Suggested Readings 319

Chapter References 320

Chapter 9

Experimental Design 323

Principles of Experimental Design 324

Setting Up a Good Research Hypothesis 326

Are fMRI data correlational? 328

Confounding factors 329

Good Practices in fMRI Experimental Design 332

Blocked Designs 333

Setting up a blocked design 333

Box 9.1 Baseline Activation in fMRI: The Default Mode Network 336

Advantages and disadvantages of blocked designs 340

Event-Related Designs 344

Principles of event-related fMRI 346

Advantages of event-related designs 350

Box 9.2 Efficient fMRI Experimental Design 352

Mixed designs 356

Summary 358

Suggested Readings 359

Chapter References 359

Chapter 10

Statistical Analysis I: Basic Analyses 363

Basic Statistical Tests 365

Contrasts: Comparing experimental conditions 366

Model-building: Predicting the fMRI signal from the experimental design 370

Regression Analyses 372

The general linear model: An overview 373

Constructing a design matrix: Regressors of interest 374

Box 10.1 Periodic Activation Evoked by Blocked Experimental Designs 376

Constructing a design matrix: Nuisance regressors 380

Modeling neuronal activity 382

Modeling hemodynamic convolution 382

Contrasts 385

Assumptions of the general linear model 387

Corrections for Multiple Comparisons 388

Calculating the significance threshold 389

Permutation testing 391

Estimating the number of independent tests 392

Cluster-based thresholding 393

Region-of-Interest Analyses 394

Intersubject Analyses 397

Group and parametric effects 400

Box 10.2 Reverse Inference 401

Displaying Statistical Results 404

Summary 408

Suggested Readings 408

Chapter References 409

Chapter 11

Statistical Analysis II: Advanced Approaches 411

Data Exploration Approaches 412

Principal components analysis (PCA) 412

Independent components analysis (ICA) 413

Partial least squares (PLS) 420

Between-Subjects Correlations 421

Correlations evoked by interactions:

Hyperscanning 422

Correlations evoked by common experience 423

Functional Connectivity Approaches 426

From coactivation to connectivity: A conceptual overview 427

Resting-state connectivity 429

Box 11.1 Increasing the Scale of fMRI Research: The Human Connectome 431

Psychophysiological interactions 433

Inferring causality from fMRI data 435

Combining fMRI and DTI 440

Prediction Approaches 442

Predicting variation among individuals 443

Box 11.2 Rapid Analyses of fMRI Data: Real-Time fMRI 444

Predicting variation in behavior 448

Pattern classification using machine learning algorithms 450

Capabilities and challenges of fMRI pattern classification 454

Summary 458

Suggested Readings 458

Chapter References 459

Chapter 12

Advanced fMRI Methods 463

The Constant Pursuit of Spatial Resolution 464

Ultrahigh-resolution structural MRI: Differentiating cortical layers 464

High-resolution fMRI: Inferring causality 467

Ultrahigh-resolution DTI delineates cortical columns 468

Innovative array coils that enable high spatial resolution and fidelity 469

The Constant Pursuit of High Temporal Resolution 472

Compressed sensing 472

Multi-band imaging 474

Advanced fMRI Contrast Mechanisms 476

Imaging with SPIO nanoparticles to enhance sensitivity 476

Ion-gated contrast 477

pH-dependent contrast 479

Neuroelectromagnetic contrast 480

Summary 482

Suggested Readings 482

Chapter References 483

Chapter 13

Combining fMRI with Other Techniques 485

Cognitive Neuroscience 485

Strategies for research in cognitive neuroscience 487

Manipulating Brain Function 488

Direct cortical stimulation 488

Transcranial direct current stimulation (tDCS) 492

Transcranial magnetic stimulation (TMS) 493

Brain lesions 496

Combined lesion and fMRI studies 499

Probabilistic brain atlases 500

Brain imaging and genomics 502

Measuring Brain Function 504

Single-unit recording 504

Box 13.1 Electrogenesis 506

Properties of electric field potentials 511

Localizing the neural generators of field potentials 512

Intracranially recorded field potentials 513

Box 13.2 Localization of Function Using Field Potential Recordings 515

Scalp-recorded field potentials 517

Box 13.3 Combining fMRI and EEG/ERP Techniques 519

Magnetoencephalography (MEG) 521

Using fMRI with non-human animals 523

Summary 528

Suggested Readings 529

Chapter References 529

Chapter 14

The Future of fMRI: Practical and Ethical Issues 533

Interpreting and Presenting fMRI Data 535

Coverage of fMRI research in the popular media 536

Box 14.1 Linking fMRI to Individual Differences: The Controversy about Circular Analyses 538

Core principles for presenting fMRI research 541

Conducting fMRI Research 545

Proposing and approving fMRI research 545

Ensuring the confidentiality of fMRI data 548

Box 14.2 Incidental Findings in fMRI Research 549

Safe conduct of fMRI studies 553

Pregnancy testing in fMRI research 555

Applying fMRI to New and Controversial Topics 555

Reading minds 557

Detecting lies 559

Identifying traits 562

Box 14.3 Why Biology Matters: The Case of Self-Control 564

Advertising and marketing 566

The Future of fMRI Research (and Your Role in It) 568

Summary 570

Suggested Readings 571

Chapter References 571

Glossary G-1

Index I-1