Foreword

The greatest challenge in writing any textbook is matching the scope and difficulty of its material to the abilities and interests of the intended audience. The topics included in our textbook, *Functional Magnetic Resonance Imaging*, are drawn from the graduate and undergraduate courses we have taught at Duke University. We cover MRI physics and physiology in considerable detail, for example, because we believe that these topics are critical for any student who wishes to understand *why* fMRI works the way it does. Also, our students spend substantial time on laboratory exercises designed to reinforce concepts from the chapters and to teach the basics of fMRI data analysis. Because our courses at Duke draw students from a variety of disciplines, from psychology to biomedical engineering, we included in our textbook a similar breadth of topical coverage.

Although this approach works well for us and for our students, we recognize that students (and instructors!) differ in their interests and educational goals. An electrical engineering graduate student who is interested in medical image processing techniques will benefit from different material than an undergraduate psychology major who is evaluating whether to study cognitive neuroscience in graduate school. Like any other authors, we have been curious as to how well our textbook can be adapted for use at different institutions. Of particular interest has been the creation of new fMRI courses at liberal arts colleges—we have known many exceptional graduate students who have come from small colleges, and a goal of ours with the textbook was to create a resource for teaching cognitive neuroscience in such settings.

To get a better idea of how fMRI courses could be taught at institutions without fMRI research facilities, we asked Dr. Kevin Wilson from the Psychology Department at Gettysburg College to document his implementation of an undergraduate course using our textbook. Psychology students at Gettysburg have a rigorous research-oriented curriculum and many are very interested in cognitive neuroscience. Few, however, had prior experience with fMRI, its physics, or its biophysics, making Kevin carefully consider what material he should emphasize and de-emphasize in his course. Moreover, at the outset of his course planning, there was no software available, much less a MRI scanner, to support student research projects.

After the course's completion, we were gratified to learn from Kevin of its resounding success. Kevin was able to quickly and cost-effectively set up a laboratory for his students to analyze freely available fMRI data sets, which were taken both from the First Edition textbook CD and from Internet databases. Some topics were more challenging than others, as in most courses, but the students learned the complex material and discussed issues raised by fMRI research at a high level. His students reported that they not only gained an appreciation for how cognitive neuroscience research is conducted, but also developed new skills that would prepare them for graduate studies. In this document, Kevin has summarized his fMRI course—from the topics he selected, to the software he used for the laboratory, and to his philosophy for leading discussions. Kevin's choices of material to emphasize necessarily follow his interests and those of his students, and others might adopt a different strategy for their courses. However, the reasoning behind his course preparation will be of value to anyone creating a new course, regardless of its specific goals. We thank him for sharing what he learned while teaching, and we hope that it will be of use to others in creating their new fMRI courses.

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Implementing an
Undergraduate Laboratory Course in
Functional Magnetic Resonance Imaging

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Abstract

In the following manuscript I demonstrate the feasibility of implementing a functional magnetic resonance imaging (fMRI) laboratory course at an undergraduate liberal arts college without internal scanning facilities and with very modest resources, based on my recent experience implementing such a course using the textbook *Functional Magnetic Resonance Imaging* (Sinauer Associates, Inc., 2004). I discuss how specific topics were incorporated into lectures, including MR hardware and physics, the physiological basis of the MR signal, data acquisition, fMRI experimental design, and the preprocessing and statistical analysis of fMRI data. I also discuss how I implemented laboratory sessions that allowed students individually to analyze freely available, existing fMRI data sets. I summarize how these laboratory sessions were implemented using existing campus computer clusters, requiring only minimal software expenditures. Finally, I describe how students were able to design their own research project and collect pilot fMRI data through collaborations with researchers at a larger institution. This type of course can be implemented at virtually any institution with proper planning and preparation and is an excellent opportunity to provide advanced undergraduate students with a first-hand appreciation of one of the fastest growing techniques for research in cognitive neuroscience.

Introduction

An important goal for science education in a liberal arts context is to provide students with research opportunities that will position them competitively for admission to graduate school. In many areas of psychology, such opportunities are readily available at most undergraduate institutions. Disciplines such as cognitive neuroscience, however, present a host of challenges to this prospect. Specifically, many of the techniques used to study the neural basis of cognition are expensive and require a host of support systems and personnel that are often not available at smaller undergraduate-focused institutions. Nevertheless, introducing students to these areas of research is critical for preparing the next generation of scientists.

Cognitive neuroscience research involving functional brain imaging is a classic example of this situation. MRI scanners are expensive and are only available at relatively large research-oriented institutions (typically those affiliated with a medical center or medical school). Maintenance of such facilities requires a host of dedicated personnel including but not limited to MR physicists, engineers, and radiological technicians. The cost of scanning can be prohibitively expensive for investigators without external funding (often in excess of $600.00 per hour). Finally, the hardware and software needed to analyze large amounts of fMRI data are often beyond the budgetary limits of many smaller institutions.

While these challenges may appear daunting for anyone interested in conducting research using functional MRI, they do not necessarily apply to someone interested in offering an undergraduate research experience course in functional MRI. Providing students with the opportunity to analyze relatively small amounts of existing fMRI data does not require any of the expensive resources described above, nor does it require prior experience conducting fMRI research on the part of the instructor. In the following manuscript, I will describe such a course that I recently implemented at Gettysburg College.

The course was an advanced undergraduate laboratory in cognitive neuroscience, with a special emphasis on functional magnetic resonance imaging. It was designed to give students an advanced understanding of a broad range of topics within the field of cognitive neuroscience, including object recognition, visual attention, and memory. In addition, there was a specific focus on how fMRI has contributed to our current state of knowledge within each of these domains. In parallel, students were introduced to the theoretical and technical basis of fMRI research and were given the opportunity to design and implement a pilot fMRI experiment of their own choosing. The course was therefore not focused exclusively on learning the methodology of functional magnetic resonance imaging, but rather on the use of fMRI in investigating the neural basis of cognition.

In the subsequent sections, I describe several areas that I needed to address in implementing the course, as well as specific reflections on how *Functional Magnetic Resonance Imaging* was used to accomplish the main objectives of the course. These reflections are not meant to be prescriptive in any sense, but rather are meant to provide one example of how such a course can be implemented at an undergraduate liberal arts institution. There are countless other approaches to implementing such a course and undoubtedly every instructor will find their own method for integrating this wonderful new research tool into the scientific curriculum. Above all, this manuscript is meant to encourage anyone who is interested in implementing such a course to do so, because it is not only eminently feasible, it is also extremely rewarding for both the students and the instructor—something to which I can now attest from personal experience.

General Course Structure

Twelve psychology majors (five juniors and seven seniors) were enrolled in the course. Enrollment in all of our advanced laboratory courses is limited to psychology majors and is capped at twelve students, although I think this course could easily accommodate another four to six students, especially if teaching assistants are available. All of the students had previously completed an intermediate-level lecture course in cognitive neuroscience, as well as laboratory courses in statistics and research methods (all three were prerequisites for the course). A significant number had also taken several natural science courses to fulfill the requirements for a minor in neuroscience. Virtually none had taken a physics course. The group was therefore largely homogenous in terms of previous coursework and academic interest.

The weekly course schedule consisted of two 75-minute lectures (meeting on Mondays and Wednesdays) and one three-hour laboratory session (meeting on Tuesdays). Wednesday lectures were devoted to discussing primary research articles that used fMRI. Topics included visual attention, memory, and object recognition. Monday lectures during the first half of the semester were devoted to the theoretical basis of fMRI signal generation, data acquisition, and statistical analysis. These lectures provided a theoretical framework for the technical aspects of fMRI discussed in the subsequent laboratory sessions on Tuesdays.

During the second half of the semester, Monday lectures and the majority of Tuesday laboratory sessions were devoted to designing and implementing a research project involving fMRI. The students were allowed to choose their own topic, with instructor guidance, and were required to complete a behavioral version of the experiment (collecting data from 16–24 participants), as well as a pilot fMRI version of the experiment (collecting data from one participant).

Meeting on three consecutive days was quite demanding at times, but it proved to be very helpful in providing continuity between the lecture and laboratory sessions. The schedule also allowed students to complete their laboratory assignments with the lecture material still fresh in mind. I thought that this arrangement was actually quite practical and will arrange for a similar schedule in future semesters.

Computing Facilities

One of the first things that must be considered in designing and implementing an fMRI course is the computing environment in which data analysis will take place. Students will need to gain experience analyzing real fMRI data sets and thus will need to have access to computers and the appropriate analysis software for significant portions of the term. The hardware and software needed to implement an fMRI laboratory course are relatively modest, particularly for the small amounts of data that are used to demonstrate basic aspects of fMRI data preprocessing and statistical analysis. Nevertheless, careful planning is important and must be done prior to the beginning of the semester. I will therefore address each of these two aspects in turn.

Hardware

Gettysburg College, like most institutions, has a number of computer laboratories on campus that are available to students on a 24-hour basis, and that can be reserved for classes that have significant computing needs. Some of these computer clusters have Windows-based desktop machines, while others have Windows-based laptops. I was able to reserve one of the enhanced classrooms with laptop computers for the course. Each student was able to have their own personal laptop, although I think many of the laboratories and exercises could have been performed effectively in pairs (i.e., two students sharing one machine). The laptop computers were Dell Latitude D600s with 512mb of RAM, 1.6 GHz Pentium 4 processors, and 20g hard drives. The machines were already several years old, and although they may not be optimal for large-scale fMRI data analysis, they were more than sufficient for the small amounts of data being analyzed in any given week during the laboratory sessions. The classroom was also equipped with a desktop machine connected to an overhead projection system, which was essential for demonstrating various aspects of the analysis to the group as a whole prior to each laboratory.

Software

There are numerous software packages available for analyzing fMRI data. These packages differ in a several respects including the operating system on which they run (some are Windows based, others are Linux/Unix based), price (some are open source and free to the general public, others are commercially available), and functionality (packages differs in terms of the range of possible statistical analyses and preprocessing steps, as well as in terms of added features such as cortical flat-mapping techniques). Almost any package will enable you to explore the basic aspects of fMRI data processing and analysis required by this course, and the choice will ultimately depend on a number of individual factors, including previous experience and budgetary considerations.

In my own research, I have used SPM (Wellcome Department of Cognitive Neurology, London, UK) almost exclusively for the past six years. SPM is a set of routines for preprocessing and analyzing fMRI data that is freely available and quite popular in the neuroimaging community. There is an extensive support network for SPM users that includes an active email list-serve for technical questions, as well as many third-party “toolboxes” that provide added functionality to the main program. It is also very well documented and user-friendly, making it an ideal choice for undergraduate students who are new to fMRI.

Although SPM is freely-available, it requires MATLAB (Mathworks, Natick, MA, USA), which is a commercially-available technical computing environment and programming language. Although individual and group licenses of MATLAB are quite expensive, classroom licensing is available at very modest rates (approximately $45.00 per machine). Thus, with a modest one-time expenditure you can outfit an entire classroom of 12 or more computers with all of the software necessary to analyze fMRI data from start to finish. One other advantage of MATLAB, and therefore SPM, is that it is available on all three major operating systems (Windows, Macintosh OS, and Unix/Linux), and thus provides a truly platform-independent environment in which to preprocess and analyze fMRI data.

In addition to SPM, I also regularly use MRIcro (http://www.mricro.com) for data visualization and figure preparation. This program is very helpful for exploring MRI images and data sets and I highly recommend it for anyone interested in fMRI.

The Textbook

Below is a detailed summary of my reflections on each of the chapters in *Functional Magnetic Resonance Imaging*, First Edition, which served as the primary textbook for my course. In some cases I followed the text very closely. In other cases I used the text as a starting point for more in-depth discussions based on my own experiences. In still other cases I omitted chapters completely, based on the limitations of the course, and my educational goals. In all cases, however, I found the text to be thorough, accurate, and well documented.

Chapter 1 An Introduction to fMRI

I used this chapter as a general introduction to the textbook and to the concept of fMRI. I chose to focus on the portions of the chapter dealing with the historical predecessors to functional MRI, the growth of fMRI in cognitive neuroscience research in the past decade, the relationship between fMRI and other methods to localize brain functions (e.g., TMS), and the key concepts associated with fMRI including contrast, and spatial, temporal, and functional resolution. I did not spend much time discussing the history and evolution of magnetic resonance imaging in part because the focus of the course was on the use of fMRI in modern cognitive neuroscience research, not on the methodology of fMRI *per se*. Thus, the sections on “Early Studies of Magnetic

Resonance" and "NMR in Bulk Matter: Block and Purcell," and "The First MR Images" were only briefly mentioned.

Students found this chapter to be very accessible and easily grasped many of the theoretical concepts, such as "image contrast" and "resolution." They also reported that the overview section "Organization of the Textbook" was a useful summary of the material to come in subsequent chapters.

Chapter 2 MRI Scanners

Introducing MRI hardware was an important aspect of the course for two reasons. Students would be conducting their own fMRI research projects, so I thought that it was important that they understand the physical setup of a typical MRI facility. Secondly, I thought it was very important to stress the safety issues that are involved in conducting fMRI research, particularly those concerning the strong magnetic fields.

The textbook provides a good summary of the physical setup of a typical scanning facility used for conducting fMRI research, but I wanted to give the students a more direct exposure to a working MRI scanner. I therefore arranged for a tour of an MRI scanner at a local hospital through their educational outreach program. Almost all medical centers have an MRI facility and are willing to give tours of these facilities to relatively small (less than 20 people) groups of individuals. The tour was conducted by the chief radiological technician and lasted approximately 45 minutes. The tour started with a description of the magnet bore, and then proceeded with a description of the cryogen cooling system and the static magnetic field (we toured a 1.5T clinical scanner). The technician then provided several simple demonstrations of the static magnetic field (e.g., holding a wrench attached to a rope at arm's length) before moving the tour into the console room. In the console room, he briefly described various types of MRI contrast and then initiated a few pulse sequences with a water phantom in the bore of the magnet so that students could hear the characteristic acoustic noises associated with MRI data acquisition. Finally, the technician led the students to a radiological reading room and displayed several types of high resolution anatomical images, including some acquired with open-air MRI scanners to show the markedly different images that can be acquired with different types of MRI hardware.

This experience was invaluable for several reasons. First and foremost, it crystallized the information discussed in the textbook concerning the typical arrangement of an MRI scanning system. Secondly, it provided them with a very rich, personal, and multisensory understanding of the way in which fMRI data is actually collected. Thirdly, it piqued their interest for much of the remaining material to be discussed in the course because they were keenly interested in understanding how we would go from the relatively course brain images that we viewed during the tour to the exquisitely precise spatial maps of cognitive activity that they had seen during previous lectures.

Before we toured the local MRI facility, I felt that it was very important to discuss MRI safety. I started this lecture by having students fill out an MRI screening form (many examples are freely available on the Internet, e.g., http://www.ahicenters.com/forms/mriscreening.pdf). We then reviewed many of the major concerns as they were outlined in the textbook, including projectile effects, claustrophobia, and acoustic noise. After discussing these issues from a technical standpoint, the students watched several safety videos demonstrating these same principles. A number of such videos are freely available on the Web (e.g., http://mindbrain.ucdavis.edu/content/MRISafety.asx), and can be viewed directly within a web browser. After viewing and discussing one of these videos, the students reviewed the screening forms that they filled out at the beginning of the session. This pre-session/post-session questionnaire technique was very effective and by the end of the session, the students fully understood the reason for each of the questions on the screening form.

I spent relatively little time covering the material discussed in the "Radiofrequency Coils," "Gradient Coils," and "Shimming Coils" sections, other than to highlight the general role that each plays, and to highlight the distinction between surface and volume coils, which is a relatively important distinction in terms of designing fMRI experiments. My focus throughout this chapter was on the overall organization of an MRI scanning facility, and on the fundamental importance of safety considerations in fMRI research. Technical distinctions between the different classes of coils were therefore peripheral to my main objectives.

Chapters 3–5

The focus of my course was on the use of fMRI in cognitive neuroscience research, not on the technical and physical foundations of fMRI. The majority of the students had never taken a college-level physics course. I was therefore very reluctant to assign material from these three chapters, which cover many of the physical concepts associated with MRI signal generation and acquisition. I felt that the content of these chapters was not necessary to understand the application of fMRI in cognitive neuroscientific research, and that significant portions were too technical for the undergraduate students in my course. Moreover, several of the key concepts, including slice selection, interleaved slice acquisition, endogenous/exogenous contrast, repetition time, and echo-planar imaging were all encountered in other sections of the text or in our laboratory exercises.

An overview of the material covered in these three chapters can easily be distilled for a non-technical audience into a single 90-minute lecture. Most instructors who have personal experience conducting fMRI research should be able to discuss the general concepts presented in these chapters. For instructors who are themselves new to fMRI, or who are not as comfortable with the physical principles of magnetic resonance imaging, a colleague in the physics department should be able to prepare a lecture on this material with relatively little effort.

Chapter 6 From Neuronal to Hemodynamic Activity

One of the prerequisites for my advanced laboratory course was a 200-level lecture course on cognitive neuroscience, in which students learned about neuronal structures and signaling, basic neuroanatomy, and the vascular system. Students also learned, in very general terms, about the relationship between neuronal activity and the BOLD signal. This foundation allowed me to provide more extensive coverage of the energy demands associated with neuronal activity, cerebral vasculature and microcirculation, and a more detailed treatment of cortical neuroanatomy. Particular emphasis was given to recognizing cortical structures in different modalities, including T_1- and T_2-weighted MRI images, as well as photographic images of anatomical slices. A number of websites proved to be very useful in this regard, including the Digital Anatomist Project (http://vertex.biostr.washington.edu/da.html), the Duke University NeuroAnatomy Web Resources (http://pathology.mc.duke.edu/neuropath/nawr/nawr_index.html), the Salamon Neuroanatomy and Neurovascular Web Atlas (http://www.radnet.ucla.edu/sections/DINR/index.htm), and the Harvard University Whole Brain Atlas (http://www.med.harvard.edu/AANLIB/home.htm). These websites were also incorporated into a laboratory session devoted exclusively to viewing anatomical MRI images and localizing anatomical structures.

The students found several sections of this chapter to be particularly challenging, including the “Adenosine Triphosphate,” “Control of Blood Flow,” and “Effects of Increased Blood Flow upon Capillaries” sections. I felt that these sections, while critical for an fMRI course being taught at the graduate level, were not necessary at the undergraduate level. I therefore provided only cursory coverage of this material in my lectures, focusing instead on neuronal information transfer and cortical neuroanatomy.

Chapter 7 BOLD fMRI

This chapter, although relatively straightforward and short, was one of the most important for me in terms of explaining the physical basis of the signal being measured with fMRI, and its relationship to neuronal (and ultimately cognitive) activity. I therefore spent a great deal of time establishing the nature and characteristics of the BOLD signal, including the temporal properties (initial dip, peak, undershoot, etc.). It was essential that students understand not only the physical basis of the BOLD signal, but also what role the BOLD signal plays in the inferential logic of fMRI. I therefore repeatedly referred back to the information discussed in chapter six (particularly Figure 6.1) throughout this discussion, to stress the role of the BOLD signal in the overall chain of events from cognitive activity to fMRI.

Students found the “Astrocyte–Neuron Lactate Shuttle Model” and “Functional Studies Using Contrast Agents” sections to be quite challenging, and I will most likely not require these sections in future iterations of the course.

Chapter 8 Spatial and Temporal Properties of fMRI

The concepts of spatial and temporal resolution were clear to the students in a general sense by this point in the course, and so we spent a considerable amount of time expanding on these two aspects of the BOLD signal as described in this chapter. In discussing the concept of spatial resolution, I gave a number of examples of fMRI data collected at different spatial resolutions, and emphasized the inherent trade-offs between spatial and temporal resolution. Significantly more time was spent discussing the temporal resolution of fMRI as well as the various methods that have been used to increase it in recent years. I presented numerous examples of idealized hemodynamic responses that illustrated the concepts of scaling and superposition, to prepare students for a discussion of linearity and rapid event-related fMRI methodologies. Although the section entitled “Using Refractory Effects to Study Neuronal Adaptation” was a good, albeit brief introduction to the concept of fMRI-adaptation (fMRI-A), I felt that this approach needed considerably more coverage. I therefore expanded this section significantly and discussed data from several primary research articles that have successfully used this approach in the context of event-related fMRI.

One interesting observation that I had during this section of the course is that, on many occasions, I found myself wishing that I had a hemodynamic response simulation program so that students could, in real time, simulate brief pulses of neuronal activity and watch the changes in the BOLD response associated with those impulses, and the resulting scaling and superposition of responses. This would have been particularly helpful in a laboratory session in which students explored these concepts more fully. A brief search on the Internet did not help me to locate any such programs and so I may develop one to address these concepts more specifically in future iterations of this course.

Chapter 9 Signal and Noise in fMRI

I thought that the information in this chapter was relatively technical in nature, and only cursorily related to my course goals. Moreover, a number of the concepts overlapped with material in other chapters (e.g., the concepts of motion artifact and signal averaging). I therefore decided to omit this chapter entirely. This information would certainly be essential for a more technical course on fMRI, or for any graduate level course of functional neuroimaging. Given the focus of my course, however, it seemed appropriate to focus instead on other theoretical issues.

Chapter 10 – Preprocessing of fMRI Data

Beginning with this chapter, the distinction between the theoretical content delivered in the lectures and the practical application of this knowledge delivered in the laboratory sessions began to blur. For each step of data preprocessing, we started with a discussion of the problem that needed to be addressed (e.g., head motion, differences in slice acquisition time), and then a practical description of the steps that are typically taken to correct that problem. Relatively little time was spent on the theoretical (and in some cases mathematical) basis for these various steps. The discussion instead focused almost entirely on the pragmatics of preprocessing. I found it very useful to demonstrate visually the effects of each step of preprocessing on real data sets. In almost all cases, I showed the students "before and after" images of fMRI data that had been preprocessed. In some cases, I demonstrated relatively extreme versions of preprocessing to make a point more clearly (e.g., data sets with more than 6 mm of head motion in one direction, data sets that had smoothed with a inordinately large (~ 24 mm) smoothing kernel, etc.).

I found that my treatment of this material was heavily influenced by my choice of fMRI analysis software, perhaps more so than any other section of the course. Since SPM was used in the laboratory sessions, and since the students would eventually be using SPM to preprocess and analyze their own fMRI data sets, our discussion of preprocessing was guided almost exclusively by the manner in which these steps were implemented in SPM.

Chapter 11 Experimental Design

Some of the material in this chapter ("Basic Principles of Experimental Design," and "Setting Up a Good Research Hypothesis") was familiar to the students, all of whom had previously taken a research methods course. I therefore focused almost exclusively on the sections that were specific to fMRI experimental methods, namely, the distinction between blocked, event-related, and hybrid paradigms. Although the textbook provides specific examples of studies that implement each of these three paradigms, I found it helpful to describe additional studies, in more detail, that used each of the three approaches. I also found it helpful to engage students in a discussion, for each paper, of whether it would have been possible to draw the same conclusions using a different experimental paradigm. In each case, I had chosen studies that could not have been performed using another approach, and so this was also extremely helpful in accentuating the relative strengths of each type of design.

In the course of preparing the material for this chapter, it occurred to me that a more logical progression would be to discuss this material prior to Chapter 10, in order to present the material in roughly the same chronological order in which a researcher would consider these aspects of fMRI research. Preprocessing of fMRI data occurs *after* a suitable experimental design has been chosen and *after* data has been collected. It might therefore make more sense to discuss these issues prior to preprocessing, to reflect more accurately the chain of events involved in planning and executing fMRI research. I plan to reverse the order of presentation for these two chapters in future semesters.

Chapter 12 Statistical Analyses

As in the previous chapter, some of this material was already familiar to the students from their previous statistics course, and so we were able to focus exclusively on issues specific to the statistical analysis of fMRI data. I chose to spend relatively little time discussing the Kolmogorov–Smirnov (K–S) test, as well as correlational, data-driven, real-time, and Fourier analyses, focusing instead on the General Linear Model

(GLM). This decision, like the decisions concerning fMRI preprocessing, was also largely influenced by my choice of analysis software, since SPM implements a version of the GLM.

This was perhaps the most difficult chapter in the textbook. In working with individual students, I discovered that it was much easier to communicate the concepts associated with the GLM by using a specific example of an fMRI paradigm involving several experimental runs and a specific design matrix with numerous model parameters. Providing a concrete example was much more successful than discussing the GLM in abstract mathematical terms, and it also made it easier for students to appreciate the visual representations of design matrices that are commonly used in fMRI analyses programs such as SPM.

I made a sharp distinction between first- and second-level fMRI analyses, focusing exclusively on first-level, whole-brain statistical analyses involving the GLM in the first lecture for this chapter. Once these principles were firmly established, I then proceeded in the next lecture to discuss other forms of second-level analyses, including fixed- and random-effects analyses.

I decided to reorganize some of the material in this chapter, particularly the sections discussing Region-of-Interest (ROI) approaches, since I felt that these sorts of analyses were so fundamentally different from single- and multi-subject approaches involving the GLM. I therefore prepared an entirely separate lecture on ROI approaches that discussed extraction and selective averaging of BOLD timecourses, and the single- and multi-subject approaches to analyzing these timecourse that are distinct from whole-brain GLM-based approaches. This was another area where I had to depart substantially from the textbook, but I think it was ultimately a worthwhile departure.

Chapter 13 Applications of fMRI

I assigned this chapter as required reading, but I did not lecture on it specifically, in part because we had already spent a good deal of the semester discussing applications of fMRI, particularly with respect to attention and memory. We did discuss several of the concepts introduced in this chapter, however, including translational medicine, double dissociations, and meta-analyses.

Chapter 14 Advanced fMRI Methods

The material in this chapter seemed well suited for a graduate level treatment of fMRI methods, but perhaps too advanced for an undergraduate course. The technical and methodological focus was also not consistent with my course goals and therefore I decided to omit this chapter entirely. A graduate level course on fMRI methods would be remiss without this material, but I felt that an undergraduate course would be able to proceed seamlessly without it.

Chapter 15 Converging Operations

All of the students in this course had completed a lecture course in cognitive neuroscience, in which the multi-methodological nature of cognitive neuroscience research was heavily emphasized. The ideas represented in this chapter were therefore somewhat familiar to many of the students, although some of the techniques were presented in much greater detail in this chapter. In some cases, I found that this additional detail was quite helpful, particularly in the “Direct Cortical Stimulation” and “Transcranial Magnetic Stimulation” sections. In other cases, I found the coverage to be somewhat too technical, particularly in the “Field Potentials,” “Localizing the Neuronal Generators of Field Potentials,” “Electrogenesis,” and “Localization of Function Using Field Potential Recordings” sections. I also thought that it would have been very helpful to reproduce Figure 1.7 (which graphically demonstrates the relative spatial and temporal resolutions of these different techniques) somewhere in this chapter, to reinforce visually the relative strengths and weaknesses of each technique. Nevertheless, this chapter does an excellent job of placing functional MRI in a broader context, and accurately conveys the importance of converging evidence in cognitive neuroscientific research.

Laboratory Exercises

Laboratory sessions were intended to provide hands-on experience working with fMRI data sets as well as designing and implementing novel fMRI research. The first laboratory provided an introduction to the software that would be used over the course of the semester, including MATLAB, SPM, and MRIcro. The second session focused on MRI safety and included a tour of a local MRI facility (as described above). Subsequent laboratory sessions explored various aspects of fMRI data viewing, preprocessing, and analysis. These sessions closely paralleled the content of the textbook, and in some cases were based on the laboratories included with the text. Topics covered including basic properties of fMRI data sets, gross anatomy, preprocessing, statistical analysis of blocked and event-related data, viewing results and generating statistical maps in SPM, as well as region-of-interest (ROI) and other alternate methods of analysis. Given the goals of the course, I did not incorporate some of the more advanced laboratory topics, including "*k*-Space," "Different Image Contrast," and "Calculating Signal and Noise."

Data sets for these laboratories were drawn from several sources. In addition to the fMRI data sets provided with the textbook, which were more than adequate for each of the laboratories discussed above, I also incorporated several fMRI data sets that I had collected in connection with my own research in order to provide students with a broader range of fMRI data. There are also numerous freely available data sets available to instructors. One of the most impressive collections is the fMRI Data Bank (http://www.fmridc.org), which allows students, instructors, and researchers to download full fMRI data sets from previously published research. In addition, several fMRI packages such as SPM and AFNI provide free fMRI data sets that can be downloaded directly from the Internet (e.g., http://www.fil.ion.ucl.ac.uk/spm/data/ and http://afni.nimh.nih.gov/afni/download).

Student Research Projects

Analyzing existing data sets is an excellent, and economical, method of introducing students to fMRI research. Providing students with the opportunity to collect their own data, however, will create a more memorable and personally rewarding experience. This may not be possible at all institutions, and it will certainly increase the cost of implementing an fMRI course substantially. Nevertheless, for faculty who are already engaged in cross-institutional research collaborations, and who have the financial resources available to them, this is an excellent addition to any fMRI course.

Working in groups of four, students were able to collect pilot data for three different fMRI projects this semester. Although they were able to develop their own project, each was tightly linked to an ongoing area of research in my laboratory. Over the course of the semester, each group developed a novel research hypotheses based on our review of the literature and then implemented a behavioral version of the experiment. Based on the results of these behavioral experiments, modifications were made to each paradigm and one pilot data set was obtained using fMRI. Data was collected remotely by the instructor, and then analyzed locally by the students at Gettysburg College. Their analysis of this data, as well as a written and oral presentation of their results, was a substantial part of their course evaluation.

Summary of Student Feedback

Most of the students had an overwhelmingly positive experience this semester. Many reported that this course required more time and effort than any of course to date, but that it was also the most fulfilling. They also consistently acknowledged that this course had prepared them well for graduate-level work in this area. Below are a few representative quotations from their course evaluations at the end of the semester:

- “We leave having many tangible new skills.”
- “I liked our text a lot. It was clear and had relevant images and diagrams that enhanced the introduction of many new and detailed topics.”
- “I think I have learned more in this psychology course than any other I have taken.”

- “It was an amazing opportunity and one that I never thought I would have at this school.”

Concluding Remarks

Implementing an fMRI course in a liberal arts environment is a challenging, but rewarding endeavor for students and faculty alike. This course will make a significant contribution to virtually any scientific curriculum and can be implemented with relatively modest expenses, without internal scanning facilities, and without any prior experience conducting fMRI research. *Functional Magnetic Resonance Imaging* (Sinauer, 2004) was an invaluable resource to me and will provide instructors with all of the resources necessary to prepare such a course, should they choose to undertake a similar challenge. Here I have described one method of implementing such a course, but countless others are possible. I hope that instructors will find this manuscript useful for planning and implementing an fMRI laboratory course at their own school, and that they too will experience, first-hand, the thrill of introducing students to one of the most exciting methods of modern neuroscientific research.

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