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Functional MRI Training for Biomedical Physics and Engineering Students: Methodological Approach to Acquisition, Processing and Visualization

Abstract: Functional magnetic resonance imaging (fMRI) represents a cornerstone technique for studying brain activity and connectivity, yet its application in biomedical engineering education remains limited. The study's object was the process of teaching and learning functional magnetic resonance imaging (fMRI) methodologies within biomedical physics and engineering education. The study's subject was the methodological framework and practical module integrating acquisition, preprocessing, modelling, and visualisation of fMRI data for undergraduate training. The study aimed to design, implement, and evaluate a hands-on educational module that bridges the gap between theoretical knowledge and practical competence in fMRI workflows for biomedical students. Based on a teaching internship, a practical module was designed and implemented for undergraduate students of biomedical physics, engineering, and informatics that covered the complete fMRI workflow. The module combined an on-site visit to a radiology centre, participation in a scanning session with a simple block-design task, and a hands-on laboratory focused on preprocessing, modeling, and visualization using open-source tools. A preconfigured virtual environment with FSL and standardized data conversion via BIDS/BIDScoin enabled a reproducible pipeline from DICOM to NIfTI/BIDS and downstream modeling in FEAT. Students practiced brain extraction, spatial normalization, model specification for block designs, and interpretation of thresholded activation maps in FSLeyes. Educational outcomes included improved understanding of neuroimaging pipelines, stronger operational skills with widely used software, and higher motivation for interdisciplinary research. This work proposes a methodological framework for integrating fMRI-based training into biomedical curricula and bridging technical education with modern neuroimaging applications.

Keywords: functional MRI, biomedical physics, neuroimaging, preprocessing, visualization, education.

Abbreviations:

$BOLD$ is blood-oxygen-level dependent,

$fMRI$ is functional magnetic resonance imaging,
FSL is FMRIB Software Library,
ROI is Region of Interest.

Introduction

Functional magnetic resonance imaging (fMRI) has become one of the most important noninvasive techniques for studying the human brain. Based on the blood oxygen level–dependent (BOLD) signal, it provides a window into functional activity and network connectivity and is widely applied in neuroscience, neurology, and cognitive research (*Poldrack et al., 2011*; *Logothetis et al., 2001*). The growing role of neuroimaging in clinical practice and the biomedical sciences highlights the need for students in biomedical physics, engineering, and informatics to acquire practical knowledge of this methodology.

Traditional curricula often focus primarily on theoretical aspects of medical imaging and physics but provide limited exposure to real-world data acquisition and analysis pipelines. This gap between theory and practice is especially evident in interdisciplinary environments where biomedical engineers and physicists are expected to operate confidently across acquisition, preprocessing, modeling, and visualization stages. Addressing this gap requires integrating methodological training based on authentic neuroimaging workflows.

As part of a teaching internship, a practical module was created to introduce undergraduate students to the complete fMRI workflow. The module comprised four components: an on-site visit to a radiology centre (equipment orientation and safety briefing), participation in an fMRI scanning session with a simple block-design paradigm, an online laboratory dedicated to preprocessing and analysis in a preconfigured environment using FSL with standardized data conversion via BIDS/BIDScoin, and a closing discussion focused on reflection and recommended learning pathways.

The study's object was the process of teaching and learning functional magnetic resonance imaging (fMRI) methodologies within biomedical physics and engineering education.

The study's subject was the methodological framework and practical module integrating acquisition, preprocessing, modelling, and visualisation of fMRI data for undergraduate training.

The study aimed to design, implement, and evaluate a hands-on educational module that bridges the gap between theoretical knowledge and practical competence in fMRI workflows for biomedical students.

Based on the purpose of the study, the following tasks were solved:

- analyse the limitations of traditional curricula in biomedical physics and engineering regarding neuroimaging training;
- develop a structured teaching module that incorporates authentic fMRI workflows, including acquisition, preprocessing, modelling, and visualisation stages;
- implement the module in practice through radiology centre visits, fMRI scanning sessions, virtual laboratory training, and reflective discussion;
- assess the educational outcomes in terms of students' technical competence, ability to critically interpret activation maps, and readiness for interdisciplinary collaboration;

– outline recommendations for future improvements in scalability, reproducibility, and integration of advanced statistical approaches and software environments.

The following scientific methods are used to achieve the goals and solve the study's tasks:

1) Literature analysis of neuroimaging methodologies and educational practices;
2) Pedagogical design of a practical fMRI training module;
3) Experimental implementation through an internship-based teaching sequence;
4) Practical demonstration of fMRI data acquisition using a block-design paradigm;
5) Computational analysis with FSL tools (FEAT, BET, FLIRT/FNIRT, FSLeyes) in a preconfigured virtual environment;
6) Reflection and qualitative assessment of students' learning outcomes and skill development.

The primary objective of this methodological initiative was to move beyond theoretical familiarity and cultivate hands-on skills in data organization, preprocessing, general linear modeling, and visualization of activation maps. By engaging students in practical analysis of functional imaging data within a reproducible software ecosystem, the approach aimed to improve technical competence, encourage interdisciplinary collaboration, and increase motivation for further research.

Thus, this article describes the methodological framework and educational outcomes of teaching fMRI to biomedical physics and engineering students, emphasizing its role in bridging technical education with modern neuroimaging applications.

Results

Organization of the training and course design

The module was organized as a four-step sequence that connected theoretical preparation with authentic practice: a visit to the radiology centre with equipment orientation and safety briefing; participation in an fMRI session using a simple block-design task; a hands-on laboratory focused on preprocessing and analysis in a preconfigured environment; and a closing discussion with reflection and recommended learning pathways. To ensure reproducibility and transparent data handling, the workflow incorporated standardized conversion from DICOM to NIfTI/BIDS using BIDS/BIDScoin (*Gorgolewski et al., 2016*; *Brain…, 2023*; *BIDScoin…, n.d.*). A preconfigured virtual machine (lin4neuro) provided a unified software stack with FSL and auxiliary tools, enabling students to work in a consistent environment across different computers (*Jenkinson et al., 2012*).

Thus, the course design intentionally linked conceptual preparation with authentic data collection and standardized analysis. The sequential flow (centre → scanner → lab → reflection) reduced cognitive load, improved reproducibility through BIDS, and provided a stable environment for practice, allowing students to progress from theory to executable workflows and to consolidate skills through structured reflection. A structured overview of the module content and its components is presented in the Appendix (*Table 1*).

fMRI acquisition process and student involvement

Students were introduced to clinical-like procedures at the radiology centre using a 1.5 T system. After a safety briefing, participants completed a block-design paradigm in the scanner consisting of left-hand finger tapping. The paradigm followed a 40 s rest / 40 s task timing repeated three times (total 240 s). The imaging protocol included diffusion, BOLD fMRI, and 3D T1-weighted MPRAGE (isotropic) for normalization and localization. The session emphasized task compliance, scanner etiquette, and understanding how sequence choice and timing affect downstream modeling (*Poldrack et al., 2011*).

Thus, direct participation in acquisition familiarized students with equipment workflow, safety, task execution, and timing logic, creating a concrete foundation for subsequent preprocessing and statistical modeling. Examples of the resulting activation patterns for the finger tapping paradigm are shown in the Appendix (*Figure 1*).

Data preprocessing and analysis with software tools (FSL, lin4neuro)

The computational workflow was carried out in FSL within a preconfigured lin4neuro virtual machine, ensuring a stable and reproducible environment. Raw DICOM data were converted to NIfTI/BIDS using BIDS/BIDScoin with validation prior to analysis (*Gorgolewski et al., 2016*; *Brain…, 2023*; *BIDScoin…, n.d.*). In FSL/FEAT, students followed a step-by-step preprocessing pipeline that included brain extraction (BET), spatial smoothing, and registration first to each participant's T1 anatomy via FLIRT and subsequently to the MNI152 standard space, with optional nonlinear refinement using FNIRT.

A block-design general linear model was implemented to capture alternating periods of task and rest, and FEAT's autogenerated HTML reports were examined for quality control. Visualization was performed in FSLeyes, where students inspected activation maps in both 2D and 3D views, compared them against anatomical references, and overlaid standard atlases to better interpret the spatial distribution of activations.

Thus, a BIDS-organized workflow combined with a preconfigured VM enabled training that progressed from data conversion through preprocessing, normalization to MNI152, model specification, and visualization. Students not only practiced operational use of FSL tools (FEAT, BET, FLIRT/FNIRT, and FSLeyes), but also developed an understanding of how preprocessing and design choices influence statistical outcomes (*Friston et al., 1994*; *Poldrack et al., 2011*).

Visualization of brain activation and interpretation

Using FSLeyes, students overlaid thresholded statistical maps onto each participant's T1-weighted anatomy, adjusted intensity ranges and transparency, and interactively examined coordinates, cluster sizes, and spatial extent. This hands-on practice emphasized not only visualization but also critical inspection of potential artifacts and alignment accuracy.

Interpretation exercises focused on relating model regressors to canonical task-related activations—e.g., contralateral sensorimotor cortex during finger tapping—while stressing the limitations of single-subject inference and the need for replication across sessions or groups.

The session concluded with structured guidance on reporting standards and figure preparation for appendices. In this way, visualization and interpretation training consolidated students' ability to critically read statistical parametric maps, articulate anatomy-informed conclusions aligned with the experimental design, and recognize the bridge between data acquisition, modeling, and scientific communication (*Jenkinson et al., 2012*; *Poldrack et al., 2011*; *Figure 1A–C*).

Discussion

The core problem addressed is the persistent gap between theoretical coverage of neuroimaging and students' hands-on competence with acquisition, preprocessing, and modeling pipelines. Constraints include limited scanner access, small cohorts, and reliance on single-subject analyses, which restrict generalizability and formal evaluation of learning outcomes. Reproducibility also remains sensitive to environment configuration and data standardization, even with BIDS and a preconfigured VM (*Brain…, 2023*; *BIDScoin…, n.d.*).

Future work should implement a structured evaluation framework (pre/post testing, rubric-based map interpretation, and practical checklists) and compare delivery modes (local VM, containerized setups, or cloud workspaces) and alternative software ecosystems such as AFNI (*Cox, 1996*). Extending tasks beyond simple block designs and introducing group-level statistics would deepen methodological understanding. Incorporating open datasets, simulated fMRI for ethics and practice, and interprofessional collaboration with clinicians could further enhance realism, scalability, and impact of the training. Additionally, cluster-wise inference options such as threshold-free cluster enhancement (TFCE) may be considered in future iterations to mitigate threshold dependence (*Smith & Nichols, 2009*).

Conclusion

The implemented preprocessing and analysis pipeline enabled students to acquire operational competence with core fMRI workflows, including brain extraction, spatial normalization, and thresholded statistical mapping. Particular emphasis was placed on quality control using FSLeyes, where participants critically evaluated alignment accuracy, potential artifacts, and anatomical localization of task-related activations.

Through interpretation exercises, students successfully related regressors to canonical activation patterns, most notably contralateral sensorimotor cortex responses during finger tapping. These exercises underscored both the value of single-subject fMRI for functional localization and its limitations for broader inference, highlighting the importance of replication across sessions and subjects.

Finally, the training consolidated students' ability to connect methodological rigor with scientific communication by adhering to reporting standards and figure preparation guidelines. While limited by small cohorts and restricted scanner time, the module provides a reproducible baseline for expanding to group-level statistics, diversified paradigms, and alternative delivery modes (e.g., containerized or cloud-based environments).

In sum, the internship-based module was not only created but also tested in practice, providing a scalable blueprint for integrating fMRI-based training into biomedical curricula and bridging technical education with contemporary neuroimaging practice.

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Appendix

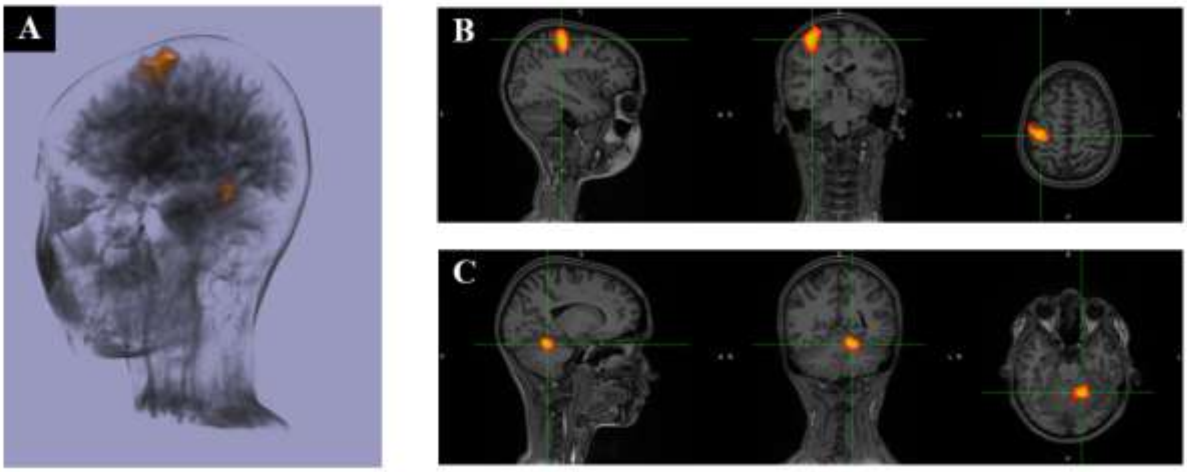

Figure 1. Left-hand finger tapping ($Z \geq 3.1$). (A) 3D volume rendering of thresholded activation; (B) orthogonal views centred on the hand knob in the right precentral gyrus (M1), showing contralateral sensorimotor activation; (C) close-up of ipsilateral activation in the superior left cerebellar hemisphere near the paravermian zone (lobules V/VI), consistent with the sensorimotor representation.

Table 1. Content and structure of the fMRI educational course

Module / Component	Objectives (Learning Outcomes)	Duration	Tools / Materials	Assessment / Output
Lecture Session	fMRI principles; clinical applications	60–75 min	Slides, key readings	Q&A, attendance
Introduction & Safety	fMRI basics; safety briefing; scanner workflow	45–60 min	Slides, MRI safety forms	Attendance, Q&A
fMRI Acquisition	Execute tasks (left-hand tapping, rest)	20–30 min/run	1.5T system, BOLD EPI sequences	Log of runs, compliance notes
Data Processing	DICOM→BIDS conversion, preprocessing, FEAT pipeline	2–3 h	BIDScoin, FSL, lin4neuro VM	QC report, GLM outputs
Data Analysis	Statistical modelling, threshold maps, ROI inspection	2 h	FSLeyes, standard atlases	Annotated figures, short essay
Interpretation & Wrap-up	Group discussion; clinical implications; next steps	45–60 min	Slides, sample cases	Written reflection, feedback