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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 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:

BET is brain extraction,

$BIDS$ is Brain Imaging Data Structure,

$BOLD$ is blood-oxygen-level dependent,
$fMRI$ is functional magnetic resonance imaging,
FSL is FMRIB Software Library,
GLM is general linear model,
QC is quality control,
ROI is Region of Interest,
$TFCE$ is threshold-free cluster enhancement.

Introduction

fMRI has become one of the most important noninvasive techniques for studying the human brain. Based on the 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 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.

Methods

The research applied a comprehensive combination of general scientific and special methodological approaches to ensure the validity and reproducibility of the proposed educational framework for fMRI training in biomedical physics and engineering. The general scientific methods included systemic, analytical, comparative, and experimental approaches aimed at identifying the gap between theoretical preparation and practical skills in neuroimaging education. The study was grounded in the principles of scientific rationality, reproducibility, and evidence-based pedagogy. The systemic approach made it possible to consider the fMRI educational module as a complex didactic system integrating theoretical instruction, clinical practice, data processing, and reflection. Analytical and comparative methods were used to review existing neuroimaging training paradigms and determine their correspondence to international educational standards in biomedical engineering. Experimental implementation served as the empirical basis for verifying the efficiency of the developed methodological sequence.

The research followed a mixed-method design that integrated elements of pedagogical experiment and applied technological testing. A teaching internship environment provided the experimental platform for implementing the proposed fMRI training module. The educational process was organized in four sequential stages—introductory theoretical preparation, on-site radiology practice, virtual laboratory for data preprocessing and analysis, and final reflection—allowing the authors to trace students' learning progress dynamically. Quantitative data were collected from practical tasks, while qualitative feedback was derived from students' reflective reports and guided discussions. This triangulation of data ensured comprehensive assessment of learning outcomes and methodological consistency.

The pedagogical experiment involved undergraduate students in biomedical physics, engineering, and informatics. Prior to practical sessions, participants received theoretical instruction on fMRI principles, safety procedures, and acquisition protocols. During on-site practice, they participated in a functional scanning session using a left-hand finger-tapping paradigm on a 1.5 T MRI system. This stage simulated real-world neuroimaging procedures, fostering comprehension of scanner operation, timing logic, and task compliance (*Poldrack et al., 2011*). The imaging protocol included BOLD fMRI and 3D T1-weighted MPRAGE sequences to ensure sufficient spatial resolution for subsequent normalization and modeling (*Logothetis et al., 2001*).

Specialized scientific methods were employed to provide technical and analytical depth to the pedagogical framework. Computational methods were central to the module, involving standardized data conversion from DICOM to NIfTI/BIDS using BIDScoin (*Gorgolewski et al., 2016*; *Brain Imaging Data Structure, 2023*). Preprocessing and analysis were conducted in the FSL environment within a preconfigured lin4neuro virtual machine (Jenkinson et al., 2012). The pipeline incorporated BET, motion correction, spatial smoothing, and registration to both individual anatomical and MNI152 standard spaces via FLIRT and FNIRT. Statistical modeling was implemented through the GLM using FEAT, enabling the detection of task-related activations (*Friston et al., 1994*). Visualization and interpretation were performed in FSLeyes, where thresholded activation maps were evaluated for alignment accuracy and anatomical validity.

In addition to technical methods, the study applied pedagogical diagnostics and reflective analysis. Students' performance was evaluated through QC reports, annotated activation maps, and written reflections, which provided insight into their understanding of preprocessing logic, statistical modeling, and the interpretation of activation patterns. Reflection served both as a qualitative research method and a pedagogical instrument, supporting metacognitive development. To strengthen methodological reliability, reproducibility was ensured by maintaining identical software environments, datasets, and task structures across participants.

Thus, the research combined pedagogical experimentation with applied neuroimaging methodology to establish a reproducible model of fMRI education. The integration of general scientific approaches with domain-specific computational tools enabled a transition from theoretical familiarity to hands-on expertise, providing an empirical foundation for enhancing the quality of biomedical engineering curricula and aligning them with contemporary neuroimaging standards.

Literature Review

fMRI has evolved into one of the most influential tools in modern neuroscience and biomedical research, enabling non-invasive exploration of brain activity through BOLD contrast (*Logothetis et al., 2001*). Since its introduction in the 1990s, fMRI has become indispensable for investigating cognitive, sensory, and motor processes, and it continues to serve as the methodological foundation for translational studies linking neural mechanisms with behaviour and pathology (*Poldrack et al., 2011*). However, despite its scientific importance, educational integration of fMRI remains underdeveloped in biomedical engineering curricula, where emphasis traditionally lies on physics and instrumentation rather than on full data-processing workflows. Bridging this pedagogical gap requires an understanding of methodological advances in neuroimaging and their didactic adaptation.

The theoretical basis of fMRI data analysis rests upon the GLM, which provides a statistical framework for identifying task-related changes in BOLD signal (*Friston et al., 1994*). Over time, refinements of the GLM and its derivatives—such as random-effects models and cluster-based inference—have improved the accuracy and reproducibility of neuroimaging findings. The introduction of TFCE further mitigated problems of arbitrary thresholding and spatial smoothing, ensuring more reliable localization of activations (*Smith & Nichols, 2009*). Mastery of these statistical approaches is essential for students of biomedical physics and engineering, as it builds a bridge between theoretical modelling and practical interpretation of brain activity.

An equally important methodological shift has been the standardization of data organization through the BIDS, which formalized the description and storage of neuroimaging datasets (*Gorgolewski et al., 2016*). BIDS promotes transparency, reproducibility, and interoperability, qualities that are increasingly demanded by the open-science movement (*Brain Imaging Data Structure, 2023*). The accompanying BIDScoin toolkit simplifies data conversion from DICOM to BIDS format, reducing the likelihood of errors and enabling cross-platform analyses. Incorporating such standards into educational settings familiarizes students with the workflows expected in contemporary neuroimaging laboratories.

The choice of software tools also plays a crucial pedagogical role. Among the most widely used packages, the FSL offers an integrated suite for preprocessing, statistical analysis, and visualization (*Jenkinson et al., 2012*). Its modules—BET for brain extraction, FLIRT/FNIRT for registration, and FEAT for modelling—provide a complete ecosystem for practical training. FSL's open-source nature aligns with the didactic goals of reproducibility and accessibility, allowing students to gain hands-on experience without reliance on proprietary platforms. Complementary toolkits such as AFNI (*Cox, 1996*) extend analytical possibilities and encourage comparative understanding of different computational ecosystems.

The growing emphasis on reproducibility in neuroimaging research has fostered the development of preconfigured virtual environments such as lin4neuro, which encapsulate all necessary dependencies for running FSL and related tools. These environments minimize configuration variability and make it feasible for students to replicate complex workflows on their personal computers. Such reproducible pipelines have transformed the pedagogical landscape of biomedical physics education by enabling scalable and ethically safe training with anonymized or simulated datasets.

Educationally, the integration of neuroimaging practice within biomedical curricula reflects a broader trend towards interdisciplinary learning. The intersection of physics, engineering, and neuroscience demands not only technical competence but also interpretive skills in data visualization and critical reasoning (*Poldrack et al., 2011*). Visualization tools like FSLeyes have become vital in fostering spatial understanding of brain function, linking statistical maps to anatomical landmarks. Moreover, structured training in reporting standards and figure preparation prepares students for participation in scientific communication and publication.

Overall, the literature converges on the necessity of combining methodological rigor with pedagogical innovation. Contemporary research underscores that teaching fMRI should go beyond theoretical instruction by involving authentic data, standardized workflows, and reflection-based learning. The adoption of open-source tools, standardized formats such as BIDS, and reproducible virtual environments aligns education with the best practices of modern neuroimaging. Consequently, integrating such frameworks into biomedical engineering programs not only enhances technical proficiency but also cultivates a research culture grounded in transparency, collaboration, and critical inquiry.

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 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.

Conflict of Interest

The authors declare that there is no conflict of interest.

References:

BIDScoin Workflow Documentation. (n.d.). *Bidscoin.* https://bidscoin.readthedocs.io/en/latest/workflow.html

Brain Imaging Data Structure (BIDS) Specification. (2023). *Neuroimaging.* https://bids.neuroimaging.io

Cox, R. W. (1996). AFNI: software for analysis and visualization of functional magnetic resonance neuroimages. *Computers and Biomedical Research*, *29*(3), 162–173. PMID: 8812068. https://doi.org/10.1006/cbmr.1996.0014

FMRIB Software Library (FSL) Wiki. (2012). *FSL.* https://fsl.fmrib.ox.ac.uk/fsl/fslwiki/

Friston, K. J., Holmes, A. P., Worsley, K. J., Poline, J.-B., Frith, C. D., Frackowiak, R. S. J. (1994). Statistical parametric maps in functional imaging: a general linear approach. *Human Brain Mapping*, *2*(4), 189–210. https://doi.org/10.1002/hbm.460020402

Gorgolewski, K. J., Auer, T., Calhoun, V. D., Craddock, R. C., Das, S., Duff, E. P., et al. (2016). The brain imaging data structure, a format for organizing and describing outputs of neuroimaging experiments. *Scientific Data*, *3*, 160044. https://doi.org/10.1038/sdata.2016.44

Jenkinson, M., Beckmann, C. F., Behrens, T. E. J., Woolrich, M. W., & Smith, S. M. (2012). FSL. *NeuroImage*, *62*(2), 782–790. PMID: 21979382. https://doi.org/10.1016/j.neuroimage.2011.09.015

Logothetis, N. K., Pauls, J., Augath, M., Trinath, T., & Oeltermann, A. (2001). Neurophysiological investigation of the basis of the fMRI signal. *Nature*, *412*(6843), 150–157. PMID: 11449264. https://doi.org/10.1038/35084005

Poldrack, R. A., Mumford, J. A., & Nichols, T. E. (2011). *Handbook of functional MRI Data analysis*. Cambridge University Press.

Smith, S. M., & Nichols, T. E. (2009). Threshold-free cluster enhancement: addressing problems of smoothing, threshold dependence and localisation in cluster inference. *NeuroImage*, *44*(1), 83–98. PMID: 18501637. https://doi.org/10.1016/j.neuroimage.2008.03.061

Appendix

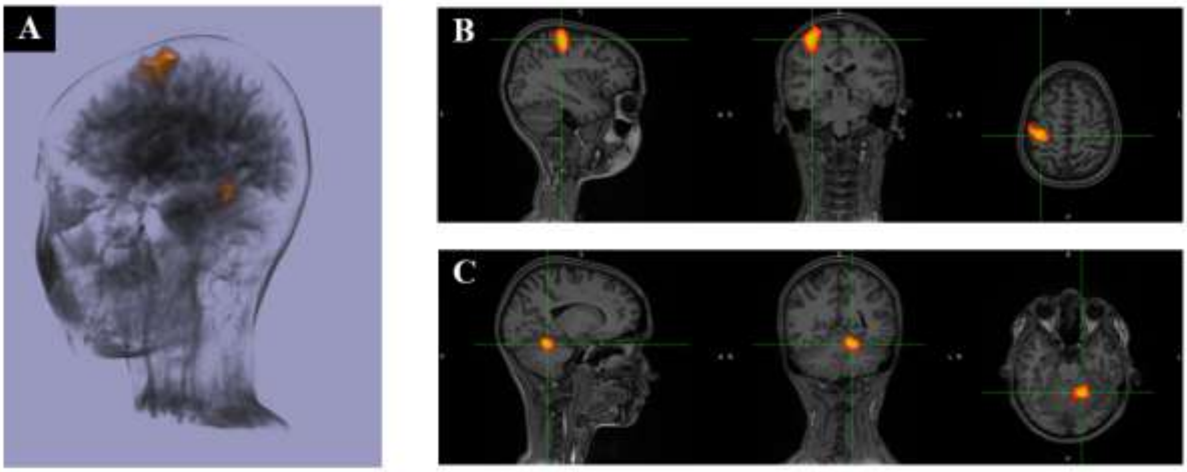

Figure 1. Left-hand finger tapping (Z ≥ 3.1). (A) 3D volume rendering of thresholded activation; (B) orthogonal views centred on the hand knob in the right precentral gyrus (M1), showing contralateral sensorimotor activation; (C) close-up of ipsilateral activation in the superior left cerebellar hemisphere 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