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Standardized data formats for interoperability in neuroimaging research.

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Introduction

Interoperability in neuroimaging research relies heavily on the adoption of standardized data formats that allow seamless sharing, processing, and integration of datasets across different research groups, institutions, and software platforms. Neuroimaging studies often generate large volumes of heterogeneous data, including structural MRI, functional MRI, diffusion-weighted imaging, positron emission tomography (PET), and associated behavioral or clinical information. Without standardized formats, data sharing becomes cumbersome, and researchers must spend significant time reformatting files to be compatible with various analysis pipelines. The lack of consistent conventions can also hinder reproducibility, as the same dataset may be stored, labeled, or organized differently by different groups. To address these challenges, the neuroimaging community has developed standardized formats and organizational frameworks that promote data transparency, reusability, and compatibility with widely used tools [1].

One of the most widely adopted standards in neuroimaging is the Brain Imaging Data Structure (BIDS), which provides a set of rules for organizing and naming files, metadata, and directory structures. BIDS was designed to be both human- and machine-readable, enabling automated pipelines to process datasets without manual intervention. The standard defines conventions for storing imaging data in formats such as NIfTI for volumetric data and accompanying JSON sidecar files for metadata, which capture acquisition parameters, task descriptions, and other essential details. By adhering to BIDS, researchers can ensure that their datasets can be easily shared with collaborators and integrated into large-scale meta-analyses. The extensibility of BIDS has also allowed it to evolve beyond MRI, with dedicated extensions for EEG, MEG, iEEG, and PET, making it a versatile standard for multimodal neuroimaging research [2].

In addition to BIDS, the Neuroimaging Informatics Technology Initiative (NIfTI) format plays a central role in ensuring interoperability. NIfTI has become the de facto standard for storing neuroimaging volumes due to its simplicity, efficiency, and compatibility with a broad range of analysis software such as FSL, AFNI, SPM, and ANTs. The format supports both single-volume and multi-volume datasets, making it suitable for static anatomical scans as well as time-series functional imaging. Metadata stored within NIfTI headers allow essential spatial information, such as voxel dimensions and

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orientation, to be preserved across processing steps. While NIfTI itself does not enforce a specific file organization structure, its widespread adoption has made it an essential building block for interoperability in conjunction with higher-level standards like BIDS [3].

Standardized data formats also extend to metadata and provenance tracking, which are essential for reproducibility and transparency. The use of structured metadata formats such as JSON, XML, and RDF allows researchers to store detailed acquisition and processing information in a way that can be easily parsed by software tools. Provenance tracking standards, such as those promoted by the Neuroimaging Data Model (NIDM), record the full history of data processing steps, including software versions, parameters, and input-output relationships. This level of documentation is critical for enabling other researchers to replicate findings or to integrate datasets into secondary analyses. Moreover, linking imaging data with clinical, genetic, and behavioral datasets requires adherence to standardized ontologies and controlled vocabularies, ensuring semantic consistency across studies [4].

Despite the clear benefits of standardized formats, challenges remain in achieving full interoperability in neuroimaging research. Legacy datasets often exist in idiosyncratic formats, requiring time-consuming conversion before they can be integrated with modern pipelines. Researchers may also face difficulties in adopting standards when working with proprietary scanner formats or specialized acquisition protocols not yet covered by existing specifications. Additionally, while BIDS and other standards have been widely embraced by the research community, consistent and correct implementation across all datasets is not always guaranteed, leading to occasional incompatibilities. Automated validation tools, such as the BIDS Validator, have been developed to help address these issues by checking datasets for compliance with the standard. However, widespread interoperability will ultimately depend on continued community engagement, education, and the integration of standards into acquisition and analysis workflows from the outset [5].

6.

Conclusion

Standardized data formats are foundational to interoperability in neuroimaging research, enabling seamless data sharing, reproducibility, and large-scale collaborative analyses. Formats such as NIfTI for imaging volumes and BIDS for dataset organization have become widely adopted, providing consistent conventions that facilitate integration across diverse platforms and research groups. Complementary standards for metadata, provenance tracking, and multimodal data integration further enhance the value of neuroimaging datasets by ensuring they remain interpretable and reusable over time. While challenges persist in converting legacy data, handling specialized acquisitions, and ensuring consistent adoption, the ongoing refinement and expansion of these standards—supported by automated validation tools and community-driven development—will continue to strengthen the foundations of open and interoperable neuroimaging science

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