

# Open science in electroencephalographic research

**Abstract**—Open science is a topic that has continually attracted more and more attention over the past two decades. This is aided by factors such as accumulation of findings on importance of transparency in science for reproducibility and replicability of findings and the development of technology which make efficient sharing of more and more research information from open research protocols to supplementary files with detailed descriptions of statistical results. The aim of this paper is to provide a review of contemporary projects, initiatives, and research in the domain of open science in electroencephalographic research.

**Key words**—open science; electroencephalography; EEG; reproducibility; replicability; transparency.

## I. WHAT IS OPEN SCIENCE

Broadly, open science can be understood as a movement in science formed around a core concept of accessibility of science to both to scientific community and broader public.

In the same way that accessibility can take different meanings and refer to different aspects of science, from accessibility of resources for doing scientific research to accessibility of existing knowledge in its various forms, so can scientific studies, resources, and initiatives be open in different ways. Analysing various initiatives in open science, Fecher and Friesike [1] point to five major lines (“schools”):

- 1) free availability of products of science – data, code, papers, and others;
- 2) openness to participation in scientific work – openness to contributions of others and collaborative approach to generating scientific knowledge, particularly through forming large teams with various fields of expertise and from diverse backgrounds;
- 3) in line with the previous two, making science accessibly to broader public, which includes both access to doing science (e.g., through citizen science) and to presenting scientific knowledge in forms that lay public can understand;
- 4) accessibility of infrastructure for scientific endeavours – forming diverse free resources and tools needed for research and open science in practice, from platforms for sharing open data and code, to public access to supercomputer services for advanced computing analyses;
- 5) finding new ways to evaluate scientific contributions that will be more comprehensive than traditional measures such as citation indices, which will consider contributions to (open) science that are currently undervalued.

Summarizing a large number of definitions of open science, Vicente-Saez and Martinez-Fuentes [2] extract four core characteristics of open science, three of which can be recognized in the description above (accessibility, sharing of research products from all its stages, and collaboration), and the fourth one points to an additional important aspect of open science – transparency. Transparency refers to making

information from the entire research process available, and in this sense it is related to the first open science line described by Fecher and Friesike, but the goal of transparency is not only to allow access to products of science as a public good, but also to allow insight into and quality control of scientific work in its various stages.

### A. Why does open science matter

Benefits of transparency and accessibility of science are not limited to contributions to the enlightenment mission of science and their systematic analysis goes beyond the scope of this paper, so we will give a few examples.

Increasing accessibility of scientific resources and knowledge to the scientific and broader community allows for a more efficient and widespread utilisation of research products. It also facilitates the involvement of a larger group of researchers, especially those whose perspectives the scientific community is currently more deprived of. Incorporating different perspectives is valuable in all fields of science, but especially in areas dealing with humans, such as neuroscience.

Moreover, accessibility of products of research from its various stages, such as experimental protocols and stimuli in EEG experiments, pre-processing and analysis scripts, data, and others, provides materials for secondary analyses and meta-analytic research. It also allows for savings due to the reduction of redundancy. This is because laboratories do not have to independently develop resources that have been shared from scratch. From the perspective of transparency, open science practices allow better insight and quality control of research, as well as a larger replicability of methods. Larger replicability of methods allows for testing replicability, robustness and generalizability of results. This ensures, for example, that time and resources are not wasted, and the progress of science is not slowed down by redundant efforts in misguided directions (e.g., see the example by Van Dang in cancer research [3])."

## II. OPEN SCIENCE PROJECTS AND RESEARCH IN EEG

In the following section, current research and projects contributing to the development of open science practices in the field of electroencephalography (EEG) will be presented. By their nature and connection to open science, they are quite diverse – some create openly accessible resources for scientific work, others generate (open) resources for the implementation of open science practices in work, and others engage in open science by, for example, being open to contributions from the broader scientific community.

### A. Open resources for standardizing scientific communication within EEG

The increasing complexity of EEG methods and the sharing of a growing amount of information through open science practices pose a challenge for researchers on how to

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clearly and thoroughly communicate all necessary information to ensure usability and searchability in the growing forest of information [4].

As a result, in this field, a whole range of initiatives of various kinds has been launched with the goal of standardization, primarily of data and reporting. What is common to all these projects is (1) a collaborative and iterative approach to the development of standards, as feedback and contributions are sought through various collaboration opportunities, from conferences, to public calls, to scientific hackathons, and (2) the free availability of standards, tools for compliance with standards, and other accompanying products of these initiatives.

*EEG-BIDS* [5] is a standard for data organization that prescribes what a dataset from an EEG experiment should contain, how files and data within files should be named, formatted, how they should be organized in folders, and what accompanying metadata should be preserved and in what format. This enables both the comprehensibility of publicly available or shared EEG experiment data and facilitates the meta-analysis of datasets from different laboratories. Many public EEG databases also seek compliance with this standard. It was formed following the example of the BIDS standard in the field of magnetic resonance [6], which served as an inspiration for the formation of similar standards in a broader range of neuroscience areas.

The standardized *preregistration template for ERP research* [7] aims to provide an easier and more comprehensive report of all aspects of event-related potentials (ERPs) experiments that need to be considered during pre-registration. Due to the complexity of ERP research, it often happens in practice that some information is overlooked in the description of methods [8], so this template is helpful for researchers who want to write a thorough and unambiguous pre-registration plan. The ERP template is the first and currently the only template of its kind in the EEG field.

*ARTEM-IS* [9] is a project of an International Neuroinformatics Coordinating Facility (INCF) working group, with the aim of supporting thorough and transparent reporting on EEG experiments by creating standardized forms to describe their methods. Currently, a form for ERP [10] is available. This ARTEM-IS form is available in the form of a web application that guides researchers through a dynamically selected set of short, unambiguous questions about the experiment method. The outcome is a thorough and standardized set of information that researchers can use as a memory aid or supplement, both during pre-registration and article writing. It is easily readable for humans and convenient for machine analysis for meta-analytic research purposes.

*COBIDAS for MEEG* [11] is a set of standards of good scientific practice in conducting and describing EEG and magnetoencephalographic (MEG) research, in the form of a living document which is continually updated. It is developed by the Organization for Human Brain Mapping (OHBM). COBIDAS for MEEG is one of a broader set of standards developed by this organization, which includes other neuroscientific methods such as MRI or eye tracking.

### B. Open lexicons of EEG and neuroscientific terms

*Interlex* [12] is an aggregator of open lexicons of neuroscientific terminology. Its purpose is to enhance communication in biomedical sciences by creating a lexicon

of biomedical terms that facilitates mapping of their various meanings. Inconsistent use of terminology is a barrier to effective communication, especially among researchers from different branches of biomedical sciences. It also poses challenges for library search and classification of scientific texts and data. Therefore, it is crucial to map meanings and their inconsistencies in order to facilitate mutual understanding, develop more advanced library search systems based on existing terminology, and create a foundation for aligning these diverse meanings. *Interlex* gathers information from multiple lexicons, smaller digital lexicon platforms, and networks of terms in the field of neuroscience, such as NIDM Terms [13], which houses terms used in the mentioned BIDS-EEG specification, among others.

### C. Collaborative research projects

In the field of EEG research, two large, collaborative projects are in progress – one on replicability of methods (*EEGManyPipelines*) and one on replicability of results (*EEGManyLabs*). Both projects build on the trend of examining replicability of research sparked by results on a large proportion of unreplicable findings in behavioural research in psychology [14].

*EEGManyLabs* [15] represents a collaborative effort to replicate seminal EEG studies (selected based on high citation rates and the assessment of the EEG scientific community) across multiple samples and a large number of participants, made possible through joining forces of a large number of laboratories.

Sparked by findings on variability in methods and its effects on study outcomes in the field of EEG and broader neuroscience, *EEGManyPipelines* [16] deals with exploring the degree of variability in pre-processing and analysis of EEG data. The goal is to understand the degree of variability in analytic approaches and its consequences for consistency of conclusions that are drawn. Therefore, 168 independent teams from 37 countries have been employed to test the same hypotheses on the same datasets, describe their analyses and results, and provide analysis scripts.

### D. Open code for presenting stimuli in EEG experiments

While any software can be used for stimuli presentation in EEG experiments with some adaptation and appropriate equipment, this task is made much easier when the presentation software has built-in options for sending triggers, which makes it easier to synchronise EEG data with events. Among open-source software that has this option, two commonly used tools are *PsychoPy* [17] and *OpenSesame*, both of which have the option to send triggers and they can be integrated with different systems for EEG acquisition. Both are based on Python (for offline experiments) and JavaScript (for experiments in browsers), and available both as standalone products with graphical user interface (GUI) and Python packages.

### E. Open code for EEG pre-processing and analysis

There are several open-source programs used for EEG pre-processing. They are designed to enable the import, pre-processing, and/or analysis of EEG data, and they differ in the programming language they are written in, user-friendliness, and the scope of use.

Currently, some of the most widely used programs in this group are *EEGLAB* [19], *Fieldtrip* [20], *Brainstorm* [21], and *MNE Python* [22]. In terms of openness, they can be divided

into three groups: fully open (MNE Python), where all functions can be used without the need for proprietary closed-source software like the MATLAB environment, open add-ons for commercial environments and software, typically MATLAB (Fieldtrip), and programs that exist both as add-ons for closed environments and as standalone fully open-source software (EEGLAB, Brainstorm).

EEGLAB is a software for EEG data pre-processing and analysis based on MATLAB, but also available in a compiled standalone version, and offers EEG data pre-processing with functions suitable for several types of EEG research, like ERP, ERSP, and source analysis. Its uncompiled version has a rich offer of add-ons, such as ERPLAB [23] or EYE-EEG [24]. In addition to having many add-ons, EEGLAB has an advantage of enabling many functions to be carried out using a user-friendly GUI, particularly in the beginning, which makes the learning curve much milder, especially for researchers who have less programming experience.

*MNE-Python* is an open-source and fully free software, because it is based on Python, and it can be used to analyse EEG as well as MEG data. Its big advantage is the option to integrate it easily with other Python packages and libraries, including tools for machine learning used for brain-computer interface (BCI) and some of the EEG analyses. On the other hand, it requires a solid mastery of Python language and environment.

*Brainstorm* is designed for analysis and visualisation of EEG data, as well as other electrophysiological measurements such as MEG or ECoG. Like EEGLAB, it is written in MATLAB and can be used with both GUI and scripts. In addition to typical EEG options, special emphasis in this software is placed on source analysis techniques and their integration with data obtained through magnetic resonance. Thanks to a very active scientific community taking part in its development, it offers a lot of functions which are regularly updated, and it is accommodating to new users.

*Fieldtrip* is a MATLAB package for analysis of EEG and other electrophysiological data. It does not have a standalone version or GUI, so its use requires knowledge of MATLAB programming language, but it offers options which are not available in other above-mentioned packages, and it can be integrated with other tools written in MATLAB.

In addition to packages and programmes for EEG preprocessing, there is a number of packages for advanced EEG statistical analysis. Two examples are provided below.

*Mass Univariate ERP Toolbox* [25] is an EEGLAB add-on, which can be used in MATLAB environment. It can be used to conduct statistical analyses based on permutation tests and finding statistically significant clusters [26]. This approach is particularly useful for ERP studies in which there are no a priori expectations on the time window and/or location of effects.

*RAGU* [27] is another MATLAB package which can be used for EEG and MEG research. It is designed for comparison of similarities and differences between entire topographies of electrical fields, whose significance is being tested in each time point using a statistical approach known as topographical analysis of variance (TANOVA). Currently, RAGU can be used for research designs with two within-subject and one between-subject factors (with an unlimited number of factor levels).

## F. Open code for EEG acquisition

Unlike the relatively rich offer of open-source EEG preprocessing and analysis software, the offer in the domain of EEG acquisition is more scarce and relatively recent. One of the key reasons for this is most likely the fact that there was not much need for something like that until recently because all EEG hardware companies provide accompanying acquisition software. However, with the developments in the fields of multimodal research and BCI, the existing acquisition software, designed for unimodal recordings and specific hardware, is no longer powerful and flexible enough.

One of the examples of such tools is *OpenVIBE* [28], brain-computer-interface multi-purpose software, which can be used for acquisition among other things. OpenVIBE has the advantages of being in use for a while, having a pool of users in the BCI research community, and being validated for use with many of the EEG acquisition systems.

## G. Other open EEG resources

*ERP CORE* [29] can be described as a „multi-purpose“ open resource, combining several above-described goals. It is an open collection which contains experimental scripts and pre-processing and analysis instructions for several of the most influential ERP experimental paradigms. In addition, it includes a high-quality dataset with recordings from 40 participants who took part in these experiments. The purpose of this collection is not only to save time and make designing studies easier, or provide teaching resources, but also to provide groundwork for a future standardization of experimental procedures and analytic protocols in the field of ERP, in which lack of consistency is in some cases hindering advancement of science.

## H. EEG and neuroscientific events inspired by open science

Open science infrastructure in the field of EEG goes beyond open code or data, to include other types of infrastructure, such as innovative scientific events.

*Neuroscience hackathons (brainhacks)* are events which combine characteristics of work meetings, hackathons, and scientific conferences to provide infrastructure for collaborative neuroscientific projects, including the ones involving EEG, typically devoted to advancing open science. Two large international brainhacks are OHBM Brainhack [30] and Global Brainhack [31]. One group of participants is made up of research teams and individuals which could benefit from finding new collaborators or having an opportunity and conditions for a few days of intensive collaborative work. They offer hackathon participants without projects an opportunity to take part in their work. Neither group of participants pays participation fees. Despite the name that evokes programming events, it is not a competition, and the nature of contributions and work done at hackathons is not limited to programming.

## I. Projects and initiatives not specific to EEG

Although it exceeds the scope of this work, it is necessary to mention that EEG researchers leverage the benefits of open science on a broader scale, which are not closely tied to EEG or neuroscience. Examples include platforms for unpublished works (preprints, e.g., ArXiv (<https://arxiv.org/>), PsyArXiv (<https://psyarxiv.com/>), bioRxiv (<https://www.biorxiv.org/>)), research preregistration [32], sharing various types of open data [32], and other initiatives aimed at providing open access

to the publication and reading of scientific papers, including radical projects like scientific piracy [33].

### III. CONCLUSION

This paper provides a brief overview of a open projects, research, and initiatives in the field of open science. They are diverse and include collaborative research, open knowledge sources such as terminological lexicons, standards for scientific communication to increase transparency in communication and curating increasingly diverse open resources, open tools and other infrastructure, such as neuroscientific hackathons.

In addition to producing open data, tools, and more, these initiatives often share a collaborative approach and openness to contributions from various sources, as evidenced by overlaps between authors and results of these projects, such as the BIDS dictionary on the Interlex platform, collaboration between ARTEM-IS and COBIDAS teams, or the participation of research teams producing many of the described solutions in neuroscientific hackathons.

In summary, these initiatives testify to growing needs for and possibilities to ensure greater transparency in scientific work, more efficient and broader collaboration among researchers, and more efficient exploration and systematization of increasingly rich and diverse data. These efforts lead to a gradual transformation of the field of EEG research towards open, or at least more open, science. This transformation is driven not only by methodological necessity but also by a culture of valuing knowledge as a public good and treasuring collaboration towards the common goal of unravelling the mysteries of the human brain's functioning.

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#### APSTRAKT

Otvorena nauka je tema koja kontinuirano privlači sve veću pažnju naučne javnosti tokom poslednje dve decenije. Tome doprinose faktori kao što su akumulacija podataka o značaju transparentnosti u naučnom radu za obezbeđivanje reproducibilnosti i replikabilnosti istraživanja i razvoj tehnologije, koji omogućava efikasno deljenje sve više podataka o istraživanjima, od eksperimentalnih skriptova do suplemenata sa detaljnim prikazom statističkih rezultata. Cilj ovog rada je da pruži pregled aktuelnih projekata, inicijativa, i istraživanja u oblasti otvorene nauke u domenu elektroencefalografskih istraživanja.

#### **Otvorena nauka u elektroencefalografskim istraživanjima**

Anđela Šoškić, Vojislav Jovanović