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Open science as a path to education of new psychophysiologists

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ABSTRACT

There is a pressing need for resources to train the next generation of psychophysiologists. Psychophysiology, and especially the subfield of cognitive electrophysiology, poses challenges for educators because it requires an understanding of complex concepts and experimental design, advanced analysis and programming skills, and access to specialized software and equipment. These challenges are common to other STEM fields as well. We present PURSUE (Preparing Undergraduates for Research in STEM Using Electrophysiology – www.PursueERP.com) as an example initiative that engages open educational practices to create and share freely available electrophysiology training materials. This model uses evidence-based pedagogy to create accessible and flexible materials, an open database with supporting lab-based training resources, and also provides instructor support during implementation. This model can be used for other areas within STEM. We review benefits and challenges of using open science research and publishing practices for training. Open science resources have benefits for both course-based undergraduate research experiences and other types of training by increasing access to publications, software, and code for conducting experiments and analyses, as well as access to data for those who do not have access to research equipment. Further, we argue that coordinated open educational practices are necessary to take full advantage of open science resources for training students. Open educational practices such as open educational resources, collaborative course building, and implementation support greatly enhance the ability to incorporate these open science resources into a curriculum.

1. Introduction

Open science is a set of practices that increases the accessibility of scientific research such that the products can be accessed freely by the public, reused, modified, and shared ("Open Definition - Defining Open in Open Data, Open Content and Open Knowledge," n.d.). Open science includes open research practices such as open data, code, and software, as well as open publications. These practices have many benefits for research scholarship, including transparency, replicability, data access for new and integrative research, broader dissemination, and increased citations (Allen and Mehler, 2019; McKiernan et al., 2016; Nosek et al., 2015; Swan, 2010; Tennant et al., 2016). Whereas scholarly benefits are well established and have transformed the way that research is conducted and disseminated, the benefits of open science practices for training and educating students have received less attention. Open science practices can increase access to a wealth of high-quality data and data analysis resources that enhance student ability to engage in authentic research experiences. However, open access alone may be insufficient for training purposes, especially for highly complex fields of study. Additional access to open *educational* resources and practices provides the needed support for instructors to utilize these materials efficiently in their courses and labs.

Open science and open educational resources enable instructors to overcome both technological and pedagogical challenges that are common to many fields within STEM (science, technology, engineering and mathematics). For example, open data are important because STEM data collection often requires specialized instruments and software that may not be available at all institutions. Access to pre-programmed experiments that run on open software negate the need for advanced programming skills and facilitate timely data collection. Access to open

Abbreviations: BIDS, Brain Imaging Data Structure for Electroencephalography; EEG, electroencephalography; ERP, event-related potentials; GUI, graphical user interface; MOOC, massive open online courses; PURSUE, Preparing Undergraduates for Research in STEM Using Electrophysiology; STEM, science, technology, engineering, and mathematics; WCAG, Web Content Accessibility Guidelines.

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educational resources that are evidence-based, engaging, and level-appropriate save faculty course-development time and provide them with vetted tools necessary to teach the complex conceptual, methodological, and analytical skills necessary for students to conduct advanced research. Finally, faculty support is necessary to ensure that materials are successfully and appropriately revised and implemented to suit the particular goals of the course and needs of the students.

In this paper we discuss the advantages of combining open science and open education through an example initiative - PURSUE (Preparing Undergraduates for Research in STEM Using Electrophysiology, www.PursueERP.com). PURSUE is a new collaborative open education project that seeks to provide innovative teaching materials and instructor support for training students in cognitive electrophysiology, a subfield of psychophysiology that links brain and behavior. Cognitive electrophysiology makes use of electroencephalography (EEG), a direct measure of brain activity recorded by electrodes placed on the scalp. This relatively low-cost method has high temporal resolution and the ability to time-lock neural signals to experimental events, producing data that yield event-related potentials (ERPs). These qualities make cognitive electrophysiology an ideal method to link brain and behavior as well as to study the time-course and organization of cognitive processing.

Although PURSUE is specific in its focus, its educational materials are relevant to many areas within STEM. PURSUE introduces students to basic research design and statistics concepts that are foundational to scientific inquiry. Moreover, many of the skills necessary for EEG analysis transfer to other neuroscience areas. For example, EEG utilizes digital signal processing methods (filtering, deconvolution, Fourier Analysis) that are common to other types of biological data. Importantly, the scope of learning involved in cognitive electrophysiology training has broad applications, integrating knowledge from neurobiology, physics, psychology, mathematics, engineering, statistics and computer science. The benefits of the PURSUE model and its open science approach can therefore be generalized to other areas within psychophysiology as well as other STEM fields.

We first describe the PURSUE model and the features of its open educational resources. Next, we discuss how PURSUE leverages current open science research practices to enhance training. Finally, we consider how PURSUE incorporates open educational practices to facilitate implementation and faculty support. We argue that PURSUE's readily available curriculum, teaching aids, and implementation support have the potential to greatly expand the utility of open science resources, and can be used as a model for other projects that wish to leverage open science resources for training.

2. PURSUE provides open educational resources

2.1. Open educational resources

Open educational resources, as defined by UNESCO (2002), refer to the "open provision of educational resources, enabled by information and communication technologies, for consultation, use and adaptation by a community of users for noncommercial purposes." Open educational resources are most often associated with free access to online course offerings (MOOCs – massive open online courses) and free online texts. However, the term may also include other supporting materials that can be used flexibly by instructors and teachers (syllabi, lecture slides, videos, assessments, software, simulations, etc.). These materials are offered free of cost and are licensed in such a way that they can be adapted and redistributed with appropriate attribution. In ideal cases, revisions and adaptations of materials are also distributed through open access venues (Downes, 2007). Open educational resources significantly reduce the cost of education for students, broaden accessibility, improve grades, and increase retention (Feldstein et al., 2012; Hilton, 2020).

Many areas of STEM are successfully building open education initiatives (see https://www.oercommons.org/hubs/open-textbooks and https://bookdown.org/home/archive/ for lists of current open-source textbooks). The topic with the most comprehensive coverage is statistics (Navarro and Foxcroft, 2018 is a particularly good example of an open education statistics text that uses open source data sets and open source software). However, open education initiatives in psychophysiology are nascent. In a recent survey of 203 faculty who conduct electrophysiology research, only 24% offered courses to undergraduates and graduates that include an EEG/ERP lab component, and that number drops to 13% when considering undergraduates alone (Bukach et al., 2015). Moreover, a shortage of training materials was a common theme among faculty comments. Indeed, 98% of respondents agreed there was a need for publicly available training materials devoted to electrophysiology principles and techniques, and 86% reported this need to be moderate or great. Recently, Luck and Kappenman published a series of videos based on the ERP Bootcamp (https://erpinfo.org/intro-to-erps-course-materials). These videos are a great asset for instructors who desire a ready-made supplement to courses and lab training that introduce ERP data processing. However, PURSUE is a more comprehensive set of open educational resources that cover both conceptual and methodological foundations of ERP experimental design and analysis. PURSUE's materials are designed specifically for undergraduates, although they are also useful for graduate-level instruction as well.

2.2. Overview of PURSUE resources

PURSUE is a collaborative initiative whose goal is to provide open educational resources for undergraduate-level training in cognitive electrophysiology using evidence-based pedagogical practices. The project is led by three principal investigators (co-authors C. M. Bukach, J. W. Couperus and C. L. Reed). Initial funding was provided by the Association for Psychological Science Teaching Fund and the James S. McDonnell Foundation, and further funding has been provided by National Science Foundation's Improving Undergraduate STEM Education program.

PURSUE is designed to provide educators with a full set of educational materials to allow them to integrate cognitive electrophysiology content into existing undergraduate-level Psychology and Neuroscience courses, as well as to develop new semester-long EEG/ERP courses. Materials are designed to provide learners with a conceptual understanding of EEG/ERP methodology as well as practical knowledge of experimental design. Class materials include lecture slides and in- and out-of-class activities. Lab units provide hands-on training for data preprocessing, statistical analysis, and interpretation. Multimedia learning tools include animations and interactive simulations to explain difficult concepts and how-to videos to demonstrate practical lab procedures. A large ERP database provides data for lab modules as well as opportunities for students to engage in authentic research, even without access to EEG instruments (see details below). The first phase of PURSUE is now complete, and several products are available on the PURSUE website (www.PursueERP.com), as indicated in Fig. 1. The second phase of the project involves assessing and revising the full-semester course materials, hosting faculty workshops to support adaptation and implementation, and completing curation and release of the PURSUE database.

2.3. Features of PURSUE's open educational resources

To be effective, open educational resources should incorporate evidence-based pedagogical practices, optimize flexibility so that materials can be adapted for a variety of teaching contexts, and be accessible to students from a variety of backgrounds and needs. According to DeVries (2013), open source teaching materials should meet several related criteria to be effective. Materials should be well organized and structured to allow easy navigation. They should include instructions, provide necessary source files, and be self-contained (i.e., avoid referencing prior content). The materials should also include learning outcomes and assessments, as well as flexible delivery options. Finally, the

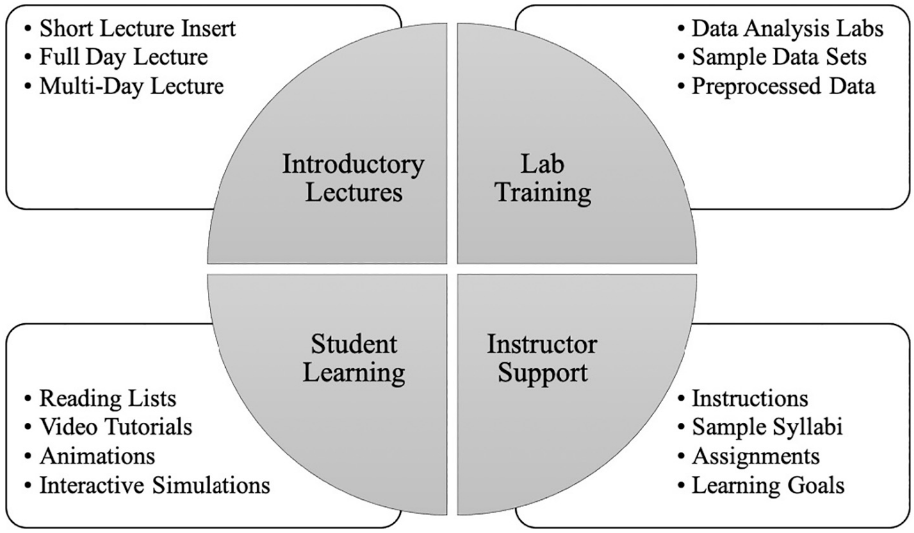

Fig. 1. List of Phase 1 resources available from www.PursueERP.com website.

materials need to be appropriately licensed. In this section we briefly discuss how PURSUE incorporates these criteria for effective open science educational resources.

2.3.1. Evidence-based practices

PURSUE materials incorporate several evidence-based practices that are part of the *How People Learn* framework (Bransford et al., 2000). First, PURSUE materials are knowledge-centered, using the backwards course design approach of starting with learning goals and assessments before developing materials (Wiggins and McTighe, 2011). Second, materials are student-centered, incorporating active learning and problem-solving activities. Third, PURSUE's course activities are community-centered, encouraging opportunities for peer interaction. Finally, the materials are assessment-centered, providing opportunities for self- and formative evaluations that help students achieve a higher level of understanding in Bloom's Taxonomy of learning (Krathwohl, 2002). PURSUE materials also include specific learning goals for each module, assessments, rubrics, and other instructor support documents.

2.3.2. Flexible delivery options

Flexible delivery is important so that educators can easily modify the materials to suit their specific needs. Consistent with recommended open educational practices, PURSUE materials are licensed under creative commons to allow users to modify, reuse, and redistribute the materials for non-commercial purposes with share-alike restrictions that maintain open access. To facilitate flexible implementation, materials are modular and organized by topic such that modules that can be selected and rearranged depending on learning goals and time constraints. Moreover, we include instructor support materials with examples of different ways that modules may be arranged. We also include flexibility within modules by providing different ways to present the same information. Instructors may modify materials to substitute specific ERP experiments and real-world applications, depending on student and instructor interests. Additionally, instructors may select among various optional activities for use in individual or group work before, during, or after class, and for remote learning. Lab materials are also designed to be easily modified. They include raw data files, subject average files for instructors who wish to skip preprocessing stages, and an Excel summary file of latency and amplitude data for those who wish to jump directly to hypothesis testing and statistical analysis. This summary file also includes a variety of individual difference measures that yield specific statistical outcomes (positive, negative or no correlation) to accommodate different data analysis learning goals and interests.

2.3.3. Accessibility

One of the challenges of designing open course materials is to ensure that they are suitable and appealing to a variety of audiences. To help accomplish this goal, PURSUE enlisted a faculty learning community of instructors from six additional collegiate institutions to complement the expertise of the principal investigators and increase the diversity of the collaboration. Because electrophysiology is a broad and complex field, recruiting faculty with different types of expertise improved the conceptual breadth and depth of our materials. When developing the materials, we also found collaborative group meetings were synergistic, leading to creative ideas that significantly improved the quality of our materials. To ensure that materials were engaging and understandable to the target undergraduate audience, we also involved student collaborators in material development and evaluation (for more details on the nature of our collaborative model, see Bukach et al., 2019).

One way to increase the effectiveness of materials for diverse audiences is through the process of revision. "Revision" is one of the 4 Rs of open licensing, along with reuse, redistribute, and remix (Hilton III et al., 2010). To incorporate revision, our collaborative process used a modification of the cycle of innovation (Santiago-Roman et al., 2011) which consists of an ongoing cycle of development, implementation, assessment, and revision across multiple teaching contexts (see Fig. 2). Whereas our initial collaborative efforts focused on increasing the effectiveness of our materials to a broad audience, our on-going revision efforts are focused on increasing cultural relevance and suitability of our materials to a more diverse set of faculty and students. To accomplish this we incorporate inclusive pedagogy strategies (Corbett, 2001) and criteria (Makoelle, 2014) that involve diverse teaching strategies and encourage students to draw upon their own experiences (Nilholm and Alm, 2010). Improving accessibility for individuals with disabilities is also an important part of the revision process. We are currently working with a professional web design company (Materiell.com) to improve the organization and navigability of our website, and increase compliance with website content accessibility standards (WCAG, "Web Content Accessibility Guidelines 2.1," n.d.). Although not all of our content will be WCAG compliant, these revisions will significantly improve the accessibility of our website.

In summary, the PURSUE project describes one way to implement effective open educational resources and to create teaching materials that are evidence-based, flexible, and accessible. Next, we examine how PURSUE leverages existing open science research practices to enhance

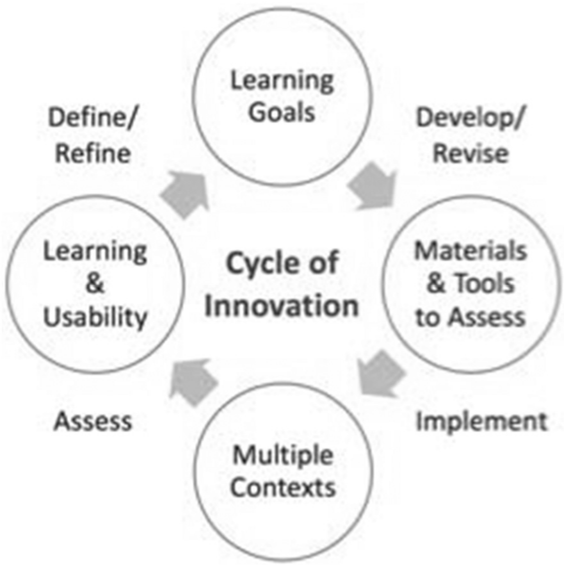

Fig. 2. PURSUE cycle of innovation.

its educational materials, and discuss ways that PURSUE will increase its use of open science practices as the project develops and evolves.

3. PURSUE leverages open science research practices for training

The materials developed for the PURSUE project are not just relevant for classroom use, but also for more advanced student training in the laboratory. The primary benefit of open science resources for training (i.e., open data, experiment code and protocols, open software for data collection and analysis, and open publications) is an increase in accessibility, particularly for students and institutions that cannot afford the expense of specialized software, equipment, and journal subscriptions. The availability of such resources allows them to be incorporated into training materials, thereby enabling students to highjack the time-consuming research process by circumventing some stages in the research stream so that they can focus on developing targeted skill sets. Moreover, utilizing open science resources also educates students about the open science framework.

3.1. Open data

Open EEG/ERP data provide students with opportunities for hands-on experience in data management, analysis, and interpretation. These experiences promote the acquisition of "transversal competencies," including digital and data literacies, critical thinking, research, teamwork, and global citizenship skills (Atenas et al., 2015). Importantly, open EEG/ERP data circumvents barriers to access, such as the need for expensive data acquisition equipment, software, and participant costs. The benefits of open-source data are particularly important for institutions that have limited resources because students can learn data analytic and computation skills that increase their preparation and competitiveness for STEM-related fields. For example, open data can be used to hone data analysis skills by replicating published findings, acquire more sophisticated analysis skills such as EEG decoding methods, or even develop new approaches to analyses potentially leading to an academic publication.

Despite these advantages, finding open data from published studies can prove to be a challenge for educators, particularly in the field of electrophysiology. The effort to publish open EEG/ERP data has lagged behind those of other neuroimaging and STEM methods. In part, resistance to publish open EEG/ERP data may be attributed to concerns over privacy; the high dimensionality and sampling rates of EEG data carry brain activity patterns unique to an individual and may provide information about that individual's mental health and personality traits (Stopczynski et al., 2014). Nonetheless, there is a small but growing set of open EEG/ERP data sets (see https://github.com/openlists/ElectrophysiologyData for a current list of available resources).

However, even when open electrophysiology data sets are found, technical challenges persist, including issues related to descriptors, formatting, and data transfer (Choudhury et al., 2014). Whether training students in the classroom or lab, data sets must have complete information and be compatible across multiple platforms. There are currently 10 major manufacturers of cognitive electrophysiology software, each with its own proprietary formats, creating barriers to data sharing and reuse (Pernet et al., 2019). Additionally, data sets must have consistent information content and organization of files, and individual files must include critical information such as trigger and condition codes. Finally, sufficient experiment information must be provided about participants and methods, as well as details of processing steps that may already have been applied. Inconsistencies within data sets can create insurmountable barriers for open use.

To overcome some of these challenges, PURSUE created a large (i.e., over 300 data sets) open EEG/ERP database designed specifically for student training. It uses open science best practices to ensure accessibility, usability, and flexibility. For those instructors who wish to develop their own training materials, this database can be used independently of PURSUE training resources. However, a major benefit of the PURSUE database is that it is integrated into the PURSUE curriculum to enhance its educational value. These features set the PURSUE database apart from previously published EEG/ERP databases.

The PURSUE project leveraged existing open resources by using previously developed CORE ERP experimental code (https://erpinfo.org/erp-core; Kappenman et al., 2021). PURSUE's database includes EEG data from a comprehensive set of six classic ERP experiments that yield seven commonly used ERP components (N170, P300, N400, N2pc, ERN, MMN, and LRP). PURSUE's ERP database can therefore be used for replication assignments of the original CORE publication findings. To increase the potential for authentic research questions, the PURSUE database also includes a rich set of demographic and individual difference measures that are clinically relevant and/or assess cognitive processing skills. The flexibility of the database allows a wide-ranging set of questions to be posed, ensuring interest to a broad audience. Moreover, its large sample size allows both basic and advanced analytic approaches.

The full release of the PURSUE database will follow the Brain Imaging Data Structure for Electroencephalography (EEG-BIDS) guidelines that were recently developed to facilitate open data sharing of EEG data (Pernet et al., 2019). Similar to the BIDS guidelines created for magnetic resonance imaging databases (Gorgolewski et al., 2016), the recommendations include suggestions for a uniform raw data format, file structure, and file naming system, as well as description files containing essential details of the experimental task and recording system. The PURSUE database will also include features relevant to educators, such as access to data files capturing different stages of the processing stream. These processed files ensure that students are better able to compare their outcomes at particular processing stages, or to skip certain stages altogether to save time or focus on particular learning goals.

A subset of the PURSUE database, along with its associated support files, has been released in advance to address pressing Coronavirus-related needs. These files include raw data that are accompanied by lab materials that guide students through basic data analyses. The database also includes ERP average files and summary data for select individual measures so that students can skip data preprocessing and simply test correlational hypotheses. Data are preselected to produce a range of correlational outcomes. However, a limitation of the pre-release is that the data have not yet been converted to meet EEG-BIDS guidelines, and thus, the currently available data are in their original recording (Brain Vision; https://brainvision.com/) and analyses (eeglab/erplab) formats.

3.2. Open protocols and code

To take full advantage of open data sets for training, educators also need tools to work with those data sets. They need access to detailed analysis procedures, whether guiding students to replicate prior studies or to conduct original research. The lack of analysis details is especially problematic for training in cognitive electrophysiology because of the complexity and number of data preprocessing steps. Even for the most basic analysis, the preprocessing stream involves a minimum of eight steps (Pernet et al., 2018). At each step, researchers must decide among several analysis options and set specific parameters that may vary by subject. Moreover, because some steps are mathematically non-linear, the order in which steps are carried out can affect analysis outcomes.

Open code and open protocols are two recent open science practices that PURSUE has leveraged for training EEG/ERP preprocessing and analyses. Open protocols describe the complete analysis procedures used for published studies. Protocols can serve as instructions that students can follow, either by implementing them in an analysis GUI (graphical user interface), or by creating a script to batch process data. Open code is an executable script that can replicate and automate the data analysis stream, limiting the need for programming skills. Students can use open code with only minor modifications (e.g., changing directory information). If open protocols and open code are also well commentated, learners can more fully understand the data processing stream and apply it successfully to data. Because the tools do not have to be created from scratch, the combination of open data, protocols, and code allows students to implement code with fewer errors and compare their analysis outcomes with those of the published results. Additionally, open code can allow students to practice introductory-level coding skills by modifying existing scripts for use on new studies or components. In the classroom or in lab training workshops, instructors can develop assignments that require the deconstruction of protocols and code. This allows students to learn about analysis and scripting as well as engage in critical analysis without the need to execute the code.

A major advantage of PURSUE is that in conjunction with the PURSUE database, instructors may use the open protocol and scripts published with the original CORE paper (Kappenman et al., 2021) or any protocols and scripts developed for PURSUE materials. PURSUE follows recommendations for creating and sharing protocols suggested by the Committee on Best Practice in Data Analysis and Sharing (Pernet et al., 2018). To be used effectively for education, PURSUE protocols and code contain all relevant choices and parameters in a format that a learner can follow. This includes comments and annotations within the code provided in a manner such that those with little experience in programming or EEG analysis can identify and understand the stage of processing that each part of the protocol or code addresses.

In addition, PURSUE materials incorporate a simplified data processing stream as part of the full semester course and lab training materials. This simplified protocol can be used to help students engage in critical thinking and deepen their conceptual knowledge of analysis procedures. It relies on the graphical user interface of open-source EEG processing software (EEGlab, https://sccn.ucsd.edu/eeglab/; and ERPlab toolbox, https://erpinfo.org/erplab) to help students focus on the conceptual steps of processing, which eliminates the need to teach scripting at the same time. It also provides a more traditional artifact rejection method, to allow novice learners to master the conceptual basics before moving to more advanced methods such as independent components analysis.

3.3. Open software and programs

Open data, analysis protocols, and code can provide the basic ingredients for training students to analyze EEG/ERP data. However, researchers and students must have access to specialized software in order to carry out data analysis procedures using these open resources. Commercial software has many advantages, including quality of support, documentation, quality assurance, performance, and regulatory and clinical compliance (Baillet et al., 2011). However, commercial software also has limitations. Commercial software may lack transparency (Gleeson et al., 2017) or the full range of analysis features required to replicate procedures carried out by other products (Lopez-Calderon and Luck, 2014). More importantly for education, the cost of commercial analysis software can be expensive. This disadvantage disproportionately affects researchers and students from underserved institutions. Even wealthy institutions may not be able to supply enough licenses for a classroom setting. Moreover, when commercial licenses are available only on institutional computers, remote learners are unable to use the software to fully participate in EEG data analysis. Freely accessible open-source software is therefore critical to large-scale and equitable training in cognitive electrophysiology.

Open source software, like other open resources, is licensed such that the public can freely use, modify, and distribute the software code (opensource.org, n.d.). Its open code allows the community to collaboratively develop the software, troubleshoot issues, and rapidly adapt it for new processing demands or approaches (Baillet et al., 2011). One popular approach to developing EEG data analysis software utilizes open-source toolboxes and plugins for commercial programming environments such as Matlab. EEGlab (https://sccn.ucsd.edu/eeglab/), ERPlab (https://erpinfo.org/erplab), Fieldtrip (https://www.fieldtriptoolbox.org/), and Brainstorm (https://neuroimage.usc.edu/brainstorm/) are examples of common open-source plugins for EEG analysis in Matlab. Although these options have certainly reduced the cost and increased the quality of EEG analysis tools, many still require the use of a commercial software environment like Matlab, which can create a significant price barrier for widespread educational use.

Other alternatives that rely on completely open environments have clear economic advantages for education. Current open environment options include Octave (https://www.gnu.org/software/octave/), Python (https://www.python.org/), and R (https://www.r-project.org/about.html). One advantage of Octave is that it is compatible with many Matlab-based scripts, including the EEGlab toolbox (for information on using EEGlab with Octave, see https://eeglab.org/others/Running_EEGLAB_on_Octave.html). MNE (https://mne.tools/stable/index.html) is a popular analysis and visualization software that runs on Python, and several EEG analysis options are available in R, such as eegkit (https://cran.r-project.org/web/packages/eegkit/index.html), eegAnalysis (https://rdrr.io/cran/eegAnalysis/), eegUtils (https://github.com/craddm/eegUtils), and erpR (https://cran.r-project.org/web/packages/erpR/index.html). For educators, it may be difficult to choose between software alternatives for analyzing EEG data. Ultimately educators will need to weigh several factors, including accessibility and cost, documentation and technical support, interoperability, analysis and visualization features, speed of processing, and the availability of educational resources to support their use. As licensing commercial EEG packages becomes increasingly expensive, open analysis options will be instrumental to making open EEG education a practical reality. We recognize this difficulty in our own PURSUE materials. In Phase 1 we implemented our experiments and data processing stream using Matlab, EEGlab and ERPlab. However, in Phase 2, we plan to create materials using open-source software that run on open environments.

Thus far, we have focused the discussion on the use of open science resources for data analysis, but open resources can also be used to teach research design and experiment programming. Open experimental software has many of the same advantages of open analysis and visualization software. First, open experimental software, such as PsychoPy (https://www.psychopy.org) and OpenSesame (https://osdoc.cogsci.nl/3.3/), that run on open environments significantly reduce student costs and increase accessibility. Open experimental code developed using open software makes it easier for students to replicate published studies or modify code to implement their own study designs using similar experimental paradigms. Moreover, open experimental code provides rich details about experiment structure that are often not described in published studies. Further, experimental code can be used for thought experiments and assignments that involve a critical analysis of the method. Deconstruction of experimental code can build programming skills, even if the code is not implemented. We note that open code for the CORE experiments are already available (Kappenman et al., 2021); however, these experiments were programmed using commercial software (Presentation software by Neurobehavioral Systems; https://www.neurobs.com/). PURSUE's future goals are to program the CORE experiments using open experimental software to increase accessibility of these important experiment design training resources.

3.4. Open access journal publications

The final set of open science practices that can be leveraged for training are those related to open access journal publications. These practices include publishing research in open access journals, archiving of process-oriented documentation such as preregistration and registered reports, and open peer review processes. Open access publication refers to "literature [that] is digital, online, free of charge, and free of most copyright and licensing restrictions" (Suber, 2012). Literature on the merits of these practices tends to focus on questions of equity (Boudry et al., 2019; Chan et al., 2009; Kovanis et al., 2016; Mittermaier, 2015; Shen and Björk, 2015; Tennant et al., 2016), economic sustainability (Legge, 2020; Tennant et al., 2016), and reform of scientific practice (Foxe and Bolam, 2017; Hazen et al., 2016; Ross-Hellauer, 2017). Although all of these questions are crucial parts of the conversation, the benefits of open journal publication practices as pedagogical tools are typically mentioned only in passing. Here we focus on the intrinsic educational value of open access publications and preregistration which we have implemented in the PURSUE initiative.

Access to journal articles not only enhances the depth and breadth of student knowledge, but is also an essential component of authentic research experiences. Moreover, engaging students in open publishing of their own research efforts is a meaningful way to educate students about open science practices. The opportunity to engage with primary materials as opposed to summaries in textbooks is critical to students developing science literacy skills. Annotated scientific papers have been used successfully to provide scaffolding for complex concepts (Kararo and McCartney, 2019). Moreover, if we wish students to participate in authentic research experiences, they need full access to primary sources in order to build appropriate background knowledge.

PURSUE leverages open access publications to increase the accessibility of its materials. For example, the use of Kappenman et al.'s open access publication about the CORE ERP experiments (Kappenman et al., 2021) facilitates replications and greatly enhances the educational value of our PURSUE database. Moreover, PURSUE uses open publishing options for its own publications, including those derived from authentic research using the PURSUE database (e.g., Couperus et al., 2021). However, despite the rising popularity of open access publishing (Piwowar et al., 2018), the majority of classic EEG/ERP papers remain accessible through subscription only, and thus PURSUE materials do not completely rely on readings that are open access. Fortunately, the modular design of PURSUE and its cycle of innovation revision process allows us to identify alternative open readings as they become available and incorporate these into our course examples, assignments, and recommended readings list. Moreover, faculty implementers are provided opportunities to suggest alternative resources through web-based feedback forms.

Whereas open publications provide students with greater access to research findings and theoretical perspectives, preregistration is an ideal tool for teaching students about the research process, open science practices, and issues such as the replication crisis (Open Science Collaboration, 2015). Preregistration involves documenting hypotheses, methods, and analysis protocols in advance of data collection or data analysis, and distinguishes these analyses from exploratory analyses that carry lesser evidentiary weight because they have occurred after data collection and/or analysis have begun. When plans for research design or analyses evolve, these can be documented in the preregistration plan. A related practice, registered reports, involves a prereview evaluation, which can improve experimental design and methods prior to data collection. (For more information on preregistration and registered reports, see Lindsay et al., 2016). Two common sites for preregistration are As Predicted (https://aspredicted.org) and Open Science Framework (cos.io/initiatives/prereg). Instructors and students can browse Open Science Framework registries (https://osf.io/registries).

The additional information provided by preregistration can be an informative supplement to journal articles for students who are learning EEG/ERP methods. Journal articles represent only a snapshot of the research process and successful writers can provide a convincing narrative, giving students a misleading impression that research is a smooth and tight trajectory of prediction, design, analysis, and outcome with a simple story line. In reality, deviations from original experimental plans due to unforeseen circumstances are common (Nosek et al., 2018). Preregistration provides a more complete picture of how research plans evolve, as well as a rationale for changes and decisions.

Entire courses and theses protocols have been developed to teach students about open science practices (e.g., Jekel et al., 2020; Sarafoglou et al., 2020). Preregistration assignments can also be used within a broader course to teach open science practices (Blincoe and Buchert, 2020). PURSUE's forthcoming full-semester course materials will include a preregistration module and assignments to introduce open science concepts and practice.

4. PURSUE uses open educational practices

Providing evidence-based open educational resources is only the first step in addressing the need to increase training opportunities in electrophysiology. Ensuring effective modifications and adoption of the materials by instructors is the key to effecting true pedagogical change (Borrego and Henderson, 2014). Thus, availability of resources alone may be insufficient to ensure broad or adequate implementation of open-source materials. Additional support at the curricular and instructor level are necessary to ensure that materials are user-friendly, adaptable, and implemented by a broad set of instructors (DeVries, 2013).

Open educational practices is a term that encompasses open educational resources and expands it to include collaborative course building and sharing of best practices in teaching and pedagogical expertise through initiatives such as faculty learning communities ("The Cape Town Open Education Declaration," 2008). Moreover, evidence suggests that successful implementation of new pedagogical approaches depends upon resource creators working with instructors to provide ongoing support through the implementation process (Fixsen et al., 2005).

Implementation of teaching innovations has been called the "missing link" of the innovation cycle (Santiago-Roman et al., 2011), and implementation support is a defining element of open educational practices. The PURSUE model facilitates implementation by continuing the cycle of innovation with additional instructor cohorts who plan to use PURSUE materials to design or modify a full-semester EEG/ERP course. The PURSUE project will host a series of workshops to support modification of PURSUE materials for individual instructor needs and contexts. As part of the workshops, the principal investigators will introduce collaborative course building and evidence-based pedagogy to ensure successful implementation. Feedback and assessments from new implementers and their students will be used to further revise PURSUE materials. We will also host brief workshops for instructors at local colleges and at international conferences to broaden the faculty learning community focused on teaching electrophysiology. It is our hope that the faculty learning community will continue to grow and provide support to new implementers, sharing their own modifications, new modules, and teaching experiences.

5. Conclusion

In this paper we have described how PURSUE incorporates open science practices to create evidence-based, accessible, and flexible resources for training in cognitive electrophysiology. Using our PURSUE project as a model, we have introduced the benefits of leveraging open science practices for training, and the need to support faculty in implementing these open science resources. The advantages of this open science model are relevant to training across STEM fields.

PURSUE is an ongoing, developing project. Many of our products will be released over the next few years. So far, the response to our open educational materials has been encouraging. Within the first six months of launching our introductory materials, we received download requests for course materials from more than 300 instructors from over 30 institutions around the world. Based on reports from these instructors, we estimate that nearly 6500 students will be trained with these materials in the first semester of use. The success of the initial product launch indicates that a model incorporating open-educational resources and practices is a promising approach to training the next generation of psychophysiologists. Of course, no one initiative can do everything. We suggest that there is a need to coordinate similar initiatives through a broader network to facilitate dissemination and instructor support. By coordinating efforts, expanding the faculty learning community, and providing cross-links on websites to other open resources, instructors – and ultimately students – will receive maximum benefits from a rich set of open educational resources.

Declaration of competing interest

None.

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