Open Science in Human Electrophysiology

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Abstract

Open science practices are gaining momentum in psychophysiological research, but at the nascent stage of this special issue in the *International Journal of Psychophysiology* there was no systematic collection of resources to support the adoption of open science practices specific to studies of human electrophysiology (EEG). The purpose of this special issue was to gather and provide resources that identify the idiosyncratic considerations and implications of open science practices specifically for studies of human EEG and event-related potentials (ERPs). Papers also show the importance of promoting good scientific practices in the application of open science principles to EEG and ERPs. This introduction to the special issue provides a roadmap for identifying the resources necessary to begin and improve the application of open science principles to EEG and ERP research. We are optimistic that open science practices will help increase the robustness, rigor, and replicability of EEG research and ultimately become the norm in studies of EEG and ERPs.

Open science practices are increasingly permeating subfields of psychology and neuroscience. Open science practices largely reflect two core principles: transparency and availability of information. We believe that applying open science principles to studies of psychology and neuroscience should contribute to a robust, rigorous, and replicable canon of research. Open science practices continue to gain momentum in psychophysiological research, but at the nascent stage of this special issue in the *International Journal of Psychophysiology* there was no systematic discussion of available resources in support of open science practices specific to studies of human electrophysiology (EEG). The purpose of this special issue was to gather resources that identify the idiosyncratic considerations and implications of open science practices specifically for studies of human EEG and to promote good scientific practices in the application of these practices to EEG. We chose human EEG as one area of psychophysiology where there is growing concern about processes, analytic pipelines, and decision points that can influence study replicability (e.g., Clayson et al., 2021c; Luck & Gaspelin, 2017), though the principles presented throughout the special issue could apply to any area of psychophysiological research.

Human EEG data are temporally and spectrally rich, and the collection and analysis of EEG data is computationally intensive and methodologically complex (Clayson et al., 2019; Kappenman & Keil, 2017). Garrett-Ruffin et al. (2021)¹ identified how the methodological complexity of EEG data contributes to challenges for the reproducibility and replicability of EEG research, broadly including challenges for preregistration, data and analysis pipeline sharing, and multi-site studies. These broad challenges provide the framework for this introduction to this special issue.

Preregistration

There are many decisions required to collect and analyze EEG data, and each decision point might impact a study's conclusions. There is no single approach for analyzing EEG data, and many different approaches to data analysis are justifiably appropriate. This flexibility in EEG data collection and analysis affords nearly limitless opportunities for discovery but provides just as many opportunities for unintentional and intentional exploitation of this flexibility. For example, Sandre et al. (2020) showed how different decisions about data processing and analyses can lead to different conclusions. They examined 72 data processing pipelines across a combination of five stages of data processing to determine how different choices impacted the error-related negativity (ERN) component of the scalp-recorded event-related potential (ERP). Each pipeline represented a common and legitimate way that ERN could be analyzed. Different combinations of processing and analysis choices led to differences in the strength of associations between ERN and post-error slowing, relationships between ERN and gender, raw amplitudes of ERN scores, and the psychometric internal consistency and test-retest reliability of ERN measurements (see also, Clayson et al., 2021c; Klawohn et al., 2020). Taken together, seemingly innocuous choices about data analysis can impact a study's conclusions in important ways (e.g., strength or direction of an observed relationship, psychometric reliability of outcome measurements). These findings also demonstrate the importance of having a clear data analysis plan before looking at the data to prevent unintentional or intentional exploitation of the flexibility inherent to EEG processing and analysis.

A preregistration of an EEG study includes study hypotheses and all methodological details. Preregistration of EEG research is a useful approach for clearly delineating between *a priori* and *post hoc* decisions (Garrett-Ruffin et al., 2021; Keil et al., 2020; Paul et al., 2021;

¹ Articles included in this special issue are underlined for ease of reference.

Saunders & Inzlicht, 2021). Paul et al. (2021) described several advantages of preregistration for EEG/ERP research, including increasing the transparency and verifiability of analyses, mitigating the potential for confirmation and hindsight bias, and improving the likelihood of publishing nonsignificant effects. They provided recommendations for preregistering ERP studies and showed examples of how to preregister methodological details in a way that is reproducible and replicable. They also addressed potential disadvantages of preregistrations, including the time required to preregister research (particularly when pursuing a reviewed preregistration; i.e., registered report), the amount of information needed to clearly describe EEG data processing and analysis, and preregistration's potential misuse. Despite these potential challenges, the use of preregistration increases the transparency of the decision-making process and allows other researchers to evaluate the capacity of a study to test a proposed hypothesis (Lakens, 2019). The template described in Paul et al. (2021) provides a much-needed roadmap for preregistering EEG studies and will facilitate the adoption of preregistration in EEG research.

Data Analysis and Pipeline Sharing

There is a pressing need for the standardization of many aspects of EEG research to make data and pipelines openly accessible. Openly sharing EEG data and processing pipelines encourages further scientific inquiry through secondary analyses, can support efforts to establish normative databases, and potentially educates researchers on newly developed techniques. However, Garrett-Ruffin et al. (2021) emphasized the variability in EEG data formats, experimental procedures, analysis workflows, and processing pipelines across studies and labs that can hinder efforts to capitalize on openly shared data. Therefore, they recommended approaches for standardizing EEG data sharing, provided examples of open-source software for paradigm presentation and data analysis, and advocated for a comparison of data analysis pipelines.

A practical step to foster the transparency of EEG data and contribute to data harmonization is to report indices of data quality and psychometric reliability (Garrett-Ruffin et al., 2021). The importance of reporting such indices is especially clear in light of how different methodological decisions can impact internal consistency (Sandre et al., 2020). Estimates of data quality provide insight into the precision of ERP measurements for a person (Luck et al., 2021), and are readily computed in open-source software, such as ERPLab (Lopez-Calderon & Luck, 2014). Estimates of psychometric internal consistency reflect whether participant ERP scores are of high enough quality to examine between-person effects/individual differences (Clayson & Miller, 2017a, 2017b). Clayson et al. (2021d) compared the advantages and disadvantages of three types of estimates: data quality, group-level internal consistency, and subject-level internal consistency. The development of subject-level internal consistency estimates for ERP scores was a novel development that fused advantages of person-specific data quality estimates with the usefulness of group-level internal consistency estimates. Subject-level internal consistency estimates characterize whether a person's ERP data is of high enough quality to be used in an investigation of individual differences. Notably, the tools for estimating subject-level reliability are openly accessible via the ERP Reliability Analysis Toolbox (Clayson & Miller, 2017a), which also includes the capability to estimate test-retest reliability (Clayson et al., 2021e) and the internal consistency of difference scores (Clayson et al., 2021a). Estimates of data quality and psychometric reliability can guide decisions about analysis and processing pipelines (Clayson, 2020; Clayson et al., 2021c; Sandre et al., 2020).

In a similar vein, Wilson et al. (2021) provided an objective, bottom-up approach to the selection of experimental stimuli for studies of ERPs. The late positive potential (LPP)

component of the scalp-recorded ERP has been considered an index of emotional attention or of motivational engagement in response to affective images, and LPP is larger for emotional images than for neutral ones (Cuthbert et al., 2000; Schupp et al., 2000). Affective images vary in emotional arousal, which is positively correlated with LPP amplitude (De Cesarei & Codispoti, 2011). Studies of LPP often rely on large databases of affective images. However, researchers are left to decide which images to include in a paradigm and might use an identical, partially overlapping, or unique set of images from any other study of LPP. To partially circumvent the need to rely solely on subjective methods for selecting images, [Wilson et al. \(2021\)](#) provided a novel application of item response theory to guide the selection of which affective images to use for further research. Item response theory can identify the optimal images for discriminating between participants with low or high emotional attention or for discriminating between groups of participants (e.g., men vs. women; healthy vs. clinical). This demonstration of item response theory is readily applicable to any study that relies on a diverse set of stimuli and opens avenues for stimulus selection using bottom-up approaches. Such bottom-up approaches support open and transparent methods, rather than simply a reliance on previous studies or tradition.

Multilevel modeling (MLM) is particularly well-suited to studies of ERPs, but MLM approaches have not yet been widely applied to ERPs. [Volpert-Esmond et al. \(2021\)](#) reviewed the use of MLM for studies of ERPs, provided guidance on critical decision-making points in the application of MLM to ERPs, and showed how to perform and report on MLM of ERP data. The application of MLM to ERPs provides the capability to go beyond the averaged ERP by examining ERP responses to specific stimuli and events or to the individual-trial level. For example, MLM can examine changes in single-trial ERPs across the course of paradigm (e.g., Berry et al., 2019; Brush et al., 2018; Volpert-Esmond et al., 2018), explore mean-variance relationships of ERP scores within persons (Clayson et al., in press), and model relationships with behavioral performance (Volpert-Esmond & Bartholow, 2021) or other ERPs (Von Gunten et al., 2018). The use of the MLM approaches afford precision in modeling effects and avoids some limitations of repeated measurements analyses of variance (ANOVA), and following the recommended reporting practices outlined by [Volpert-Esmond et al. \(2021\)](#) will provide a transparent and replicable analysis for the scientific community. All of the code for performing the analyses in [Volpert-Esmond et al. \(2021\)](#) is openly available, which serves as invaluable material for the education of researchers on the application of MLM to psychophysiological measurements.

Multi-Site Studies

Multi-site studies pool resources across different data collection sites to obtain higher sample sizes to increase statistical power and the generalizability of study findings. The #EEGManyLabs project is a recent example of a large-scale effort to promote multi-site replication of prominent findings EEG or ERP research (Pavlov et al., 2021). The coordination of multi-site efforts promote transparent research practices by encouraging quality control and the development of clear study protocols ([Garrett-Ruffin et al., 2021](#)). [Garrett-Ruffin et al. \(2021\)](#) described relevant challenges for EEG researchers, such as site differences in hardware or data processing pipelines, proposed solutions to overcome such challenges, and advocated open calls for multi-site collaborations and funding for multi-site research. Despite the potential benefits of multi-site studies for EEG researchers, they are quite rare. This work will hopefully foster more multi-site collaborations than has historically been seen in the EEG/ERP literature and ultimately improve the replicability and generalizability of our findings.

Meta-analytic techniques often pool information across existing studies to summarize an effect of interest. Saunders and Inzlicht (2021) provided a walkthrough of how to improve the credibility and rigor of meta-analyses of ERP studies. Meta-analyses are subject to the same inherent flexibility as any ERP study, and different choices about inclusion/exclusion criteria can lead to different conclusions. They provided a poignant example that illustrates the flexibility of meta-analyses by using examples of meta-analytic work on the relationship between ERN and anxiety. At least six meta-analyses have examined the ERN-anxiety relationship, and estimates range from significant, medium-sized effects ($r = -.25$; Moser et al., 2013) to nonsignificant, near-zero effect sizes ($r = -.03$; Saunders & Inzlicht, 2020). Regarding openness of scientific practices, Saunders and Inzlicht (2021) highlighted the need for preregistering meta-analyses of ERP studies, showed the application of different approaches to correct for publication bias, and promoted the use of prospective meta-analyses. Unlike a retrospective meta-analysis of existing studies, a prospective meta-analysis only includes data collected after preregistration, which allows for a truly confirmatory analytic approach. Furthermore, when the field widely adopts open science practices, Saunders and Inzlicht (2021) suggested that such adoption fosters meta-analytic work and a cumulative science to improve our understanding of prominent effects in EEG/ERP research.

Additional Benefits of Open Science Practices for ERP Researchers

All researchers face the challenge of getting eyes on their research to increase dissemination and application of any study's findings. An approach to reduce barriers to access to scientific work is to publish articles as open access, which is freely available, rather than closed access, which is behind a paywall. Two common open access routes are green open access, which is usually achieved through the posting of a preprint, and gold open access, which involves an article processing charge to the publisher. Clayson et al. (2021b) examined twenty years of human EEG studies to determine 1) whether open-access studies receive more attention in the form of citations and Altmetric mentions than closed-access studies and 2) whether there were differences in citations for green and gold open-access research. Open-access articles received more citations and Altmetric mentions than closed-access articles (i.e., open access advantage). There was no statistically significant difference in citation counts between green and gold open-access articles, and green open access articles were related to more Altmetric mentions than closed-access articles. These findings point to a benefit of publishing EEG studies as open access, as they received more attention (citations, Altmetric mentions) than closed-access articles. Notably, gold open-access articles—typically associated with expensive article processing charges—did not show a greater benefit from the open access advantage than green open-access articles. Therefore, researchers interested in broadly disseminating their work might consider posting preprints to reduce barriers for those wishing to access that work.

A readily identifiable benefit of openly sharing data, analysis workflows, and processing pipelines is access to educational materials for researchers to learn novel approaches and adopt new scientific practices. Bukach et al. (2021) described a collaborative project (Preparing Undergraduates for Research in STEM Using Electrophysiology; PURSUE, <http://www.pursueerp.com/>) that provides open access teaching materials for instructors who teach undergraduate students. PURSUE materials leverage open data, open protocols and code, open software and programs, and open access journal publications to provide an evidenced-based course for training undergraduate students in cognitive electrophysiology. Not only does the PURSUE project provide well-curated open educational materials, but this project also benefits a wide audience by breaking down several significant barriers to involvement in EEG research,

such as the need for specialized equipment, expensive software, and advanced programming skills. The PURSUE project is a clear demonstration of the way open science principles can transform the education of the next generation of cognitive electrophysiologists.

Summary

This special issue on open science practices in studies of human electrophysiology provides an impressive resource specific to EEG and ERP researchers interested in implementing aspects of open science into their work. The implementation of open science is not an all-or-nothing process, and these practices can be adopted in a piecemeal fashion. We hope that at least one topic inspires you to make your own research more open and accessible to the scientific community. In addition to the knowledge base that the work included in this special issue provides, many articles include or point to open materials and tools to foster the application of open science principles for EEG/ERP research. We are optimistic that open science practices will help increase the robustness, rigor, and replicability of EEG research and ultimately become the norm in studies of human electrophysiology.

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