

Research Program

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Artificial Intelligence in Neuroscience

EEG-GAN: A Generative Adversarial Network for Electroencephalography Data Augmentation and Classification

My research program enhances the methodological practices of electroencephalography (EEG) science with artificial intelligence. A focus of my research has been to validate the use of generative modeling for augmenting EEG datasets, while providing an open-source Python toolbox, EEG-GAN, to help researchers easily apply these techniques to their work. Specifically, EEG-GAN uses Generative Adversarial Networks (GANs) to generate trial-level synthetic EEG samples, which can serve as additional training data for neural decoding analyses. GANs are machine learning frameworks consisting of two adversarial neural network agents, trained to produce realistic continuous EEG activity. This activity is conditioned on experimental variables that capture neural features associated with the outcomes being classified. For example, depression manifests as increased alpha oscillatory activity in EEG signals, so an ideal generator would produce continuous EEG that incorporates these characteristic alpha signatures.

We validated EEG-GAN as a tool for enhancing classification performance across three classifiers and seven sample sizes, ranging from 5 to 100 participants (Williams et al., 2023). In a reinforcement learning study, we observed up to a 12% increase in decoding accuracy with as few as 5 participants. Building on this validation, we released EEG-GAN v2.0 and demonstrated its efficacy in EEG data augmentation across a large range of experimental contexts (Williams, et al., *in prep*). Specifically, we evaluated the effects of GAN-augmentation across four datasets, five classifiers, seven sample sizes, three EEG systems, and three distinct processing pipelines. It achieved up to a 16% improvement in decoding accuracy, with consistent enhancements across datasets and their respective EEG processing pipelines. Augmentations were particularly effective for sample sizes ranging from 5 to 30, significantly improving 70% of classification analyses and only impairing 4%. Further, EEG-GAN outperformed six benchmark augmentation techniques for 69% of comparisons, while being outperformed in only 3% of cases.

Our findings highlight EEG-GAN's potential as a tool for enhancing EEG decodability across various research studies. Building on this foundation, future investigations will focus on validating EEG-GAN in studies on clinical populations, brain health assessments, and advancing neurotechnology applications. Additional future directions include exploring EEG-GAN's ability to recover lost EEG signals due to excessive noise and artifacts, increasing electrode density in sparse mobile EEG systems, and developing it as an AI-driven EEG processing pipeline.

Automated Research Assistant (AutoRA): A Framework for Automating the Empirical Research Process and its Application in Model Discovery of Information Processing

There has been a rapid growth of complex datasets within psychology and neuroscience. These complex datasets pose challenges for integrating observations into quantitative models of human information processing. Other fields of research, such as physics, have proposed symbolic regression techniques as a way of automating data-driven discovery of interpretable computational models. Symbolic regression is an artificial intelligence model discovery approach that, unlike traditional regression methods that assume a predefined form of the computational model, searches for both the structure and parameters of a mathematical model to link input variables to an output variable.

Several methods of symbolic regression now exist, including the Bayesian Machine Scientist, Bayesian Symbolic Regression, and Differentiable Architecture Search. However, these algorithms have been difficult to incorporate into empirical research pipelines. The sparsity of such pipelines, particularly those incorporating symbolic regression methods, motivated the development of the open-source Python suite, Automated Research Assistant (AutoRA) (Musslick et al., 2024), which I helped create and continue to contribute as an active developer. AutoRA is a framework for automating the empirical research process including experimental design, data collection, model discovery, and documentation for open science.

Using AutoRA, we demonstrated the effectiveness of symbolic regression in recovering computational models of human information processing (Hewson et al., 2023). In this study, we validated the Bayesian Machine Scientist's (BMS) ability to recover four information processing models---Steven's Power Law, Weber-Fechner Law, Shepard-Luce Choice Rule, and Exponential Learning---using simulated data with varying noise levels. We found that BMS outperformed benchmark computational models 71% of the time, with no instances where it was outperformed. Performance converged between BMS and benchmark models only when excessive noise severely distorted the underlying signal of information processing. These results suggest that BMS holds significant potential for discovering psychological models of human information processing.

Symbolic regression could provide valuable insights into the neural mechanism underlying cognitive functioning by identifying interpretable models that link brain activity, derived by methods such as EEG, to behaviour. Future research will focus on applying symbolic regression for model discovery in EEG research, aiming to connect brain activity---such as ERP amplitudes, oscillatory power, and functional connectivity---to a broad spectrum of cognitive processes. For instance, future directions include exploring the relationship between EEG signals with the onset and severity of neurological and psychiatric disorders, as well as developing personalized treatment approaches by linking neural patterns to therapeutic outcomes, advancing precision medicine in neuroscience.

References

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