# Developing Brain-Computer Interfaces with Everyone

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**Keywords: brain-computer interface (BCI)[1], research engagement[2], open-source[3], JavaScript[4], browser[5], web[6].**



**Abstract**

Throughout its history, the field of brain-computer interfaces (BCIs) has offered people with severe motor disabilities the opportunity to engage with their environments using brain activity alone. Contemporary solutions, however, lack support for reliable evaluation by researchers, independent use by patients and their caregivers, or creative extension by students, artists, and software developers at home. This paper provides preliminary guidance on the integration of research engagement activities into BCI research to enable use at home. Alongside key principles for enabling Research Engagement Always And With Everyone, we present the initial specification for a standardized software ecosystem that could enable the rapid development of high-performance BCI applications on the Open Web. By integrating Open Web technologies alongside engagement activities in current research programs, we argue that participation in the development of a new generation of at-home BCI systems can be widened.

## 1 Introduction

Early brain-computer interfaces (BCIs) research focused on the support of adults with severe motor disabilities through neural activity translation into artificial outputs that enabled control of and communication with their environments (Wolpaw et al. 2011). Later programs and commercial ventures sought to benefit more end-users, such as the general population and specialized clinical populations, including pediatric patients (Kinney-Lang et al. 2020; Blankertz, Tangermann, and Klaus-Robert Müller 2012). Although this shift demonstrates growth it remains questionable whether potential BCI research (BCIR) beneficiaries receive benefits. Recent research indicates that only 3% of P300 BCI studies addressed sustainable end-user access to the technology (Kübler 2017). This represents a broader problem: supervised home use of BCI systems (BCISs) by people with disabilities is the norm if not the expectation. Without significant changes to current practices, the gap between the field's latest innovations and the daily lives of stakeholders may continue to widen.

Meaningful end-user engagement throughout the research process has become a promising way to improve health outcomes. While participatory research methods are well-established in human-computer interaction (HCI) and the social sciences, they remain underutilized in the biomedical enterprise (Slattery, Saeri, and Bragge 2020). User-centered design (UCD) has been promoted within BCIR to support the alignment of novel applications with the needs of end-users beyond the laboratory (Kübler, Nijboer, and Kleih 2020; Kübler et al. 2014). While this approach prioritizes design *for* users via engagement in the design and evaluation stages of a study, researchers can alternatively facilitate the production of knowledge *with* those who are or may become active users of BCISs (which, for our field, might include anyone with a brain) involved as full-fledged "knowledge users" throughout the development process, who both contribute to and receive the outputs of ongoing research (Jull et al. 2019). We argue for adopting the motto *Research Engagement Always And With Everyone (REAAWE)* to support both the empowerment of end-user populations and the direct translation of BCISs to the homes of many.

Existing technological infrastructure in BCIR is not prepared to support REAAWE. While general-purpose software platforms, such as BCI2000 and OpenVibe, have brought significant transformation to the field by allowing researchers to validate their research contributions on standardized, high-performance pipelines, they were designed with professional researchers and software engineers as their primary end-users (Schalk et al. 2004; Renard et al. 2010). As such, modern BCI software has a high barrier to entry that hinders use and adoption—much less robust participation and co-design—for those without strong technical backgrounds including artists, students, and people with disabilities (Stegman et al. 2020). Ongoing interdisciplinary research has subverted this approach by using modern web technologies for simplified distribution and development of BCISs beyond laboratory environments.

We argue that broad uptake of REAAWE in the BCI community will not only require a change in mindset, but also a change in platform towards web browsers and the affordances of the Open Web. In the following sections, we present four key principles for supporting REAAWE in BCIR, as well as our initial specification of a web-based software ecosystem designed for this goal.

## 2 Key Principles to Enable Research Engagement in BCIR

Broad uptake of REAAWE could support the participation of a wider audience in the development of novel BCISs for home use. Although end-user engagement is linked to positive outcomes, activities throughout clinical research have been fragmented and unsustainable (Manafo et al. 2018). Several studies characterized best practices for the support of sustainable engagement. These include *foundational principles* (e.g., cultivation of mutual respect, trust, openness) and *specific activities* (e.g., co-learning, regular bidirectional communication, compensation, reimbursement of out-of-pocket expenses, patient partners selection based on their skills and interests, role clarification, early stakeholder involvement in research) (Harrison et al. 2019; Heckert et al. 2020). We argue that BCIR engagement will be most effective by seeking to engage *always and with everyone* with a brain who can benefit from and contribute to the latest research innovations.

We present four principles for broadening BCIR participation adapted from existing best practices in REAAWE (Table 1). These principles have been informed by several engagement activities organized via the Brains@Play Initiative to purposely "expose" non-technical stakeholders to BCIR.

**Table 1.** Key principles for enabling Research Engagement Always And With Everyone (REAAWE) in BCI research.

| **Principle** | **Anticipated Outcome** | **Brains@Play Activity** | **Technical Corollary** |
|---|---|---|---|

| | | | |
|---|---|---|---|
| **Non-Technical Engagement** | Innovative ideas from artists, students, and people with disabilities. | Brains and Games International Design Fiction Competition | Zero dependencies |
| **Simple Research Infrastructure** | Technology that can scale to a large network of users. | Livewire: A Stimulating Night of Neurotechnology | Simplified distribution |
| **Strong Partnerships** | Uptake of novel applications in the home. | BCI Game Jam 2021: Multiplayer Madness | Continuous data collection |
| **Open Prototyping** | Public contributions to critical science and health infrastructure. | The Brains@Play Platform | Community contributions |

## 2.1 Non-Technical Engagement

Wider participation of artists, students, and people with disabilities in BCIR could drive significant innovation in home-use systems. Students and artists have historically been enabled to participate in software development through the release of easy-to-use development platforms such as Max/MSP, Processing, and Unity (Reas and Fry 2006). People with disabilities have also developed innovative resources, including the Accessible Player Experience guidelines and the Xbox Adaptive Controller by collaborating with charitable organizations such as the AbleGamers Foundation, which has enabled thousands of children and adults with limited mobility to play video games at home (Ellis and Kao 2019). Audience engagement could produce diverse data from artistic endeavors, small-scale formal evaluation, and independent use outside of the laboratory. The use of participatory methods (e.g., co-creation workshops, cooperative prototyping sessions oriented around the home where many people with disabilities spend their time) could be particularly effective to construct “third spaces” where research outputs truly integrate developer and end-user perspectives (Muller and Druin 2003). While technology might be an expected REAAWE outcome, foundational principles may be more effective for encouraging participation instead of technical prototypes.

Brains@Play recruited diverse BCI stakeholders through public engagement events focused on ethics and design, including the “Brains and Games International Design Fiction Competition" and invited participants to submit their ideas for speculative brain-responsive multiplayer games (Brains@Play 2021a). This event drew the attention of ~50 experts in neuroscience, neuroethics, and interactive media to the submissions of 20 remote teams—largely composed of international young adults and children. Top-ranked teams received guaranteed development support and OpenBCI Low-cost Biosensing Starter Kits. We encouraged our community to consider the consequences of technology development without a guaranteed technical outcome.

## 2.2 Simplified Research Infrastructure

Long-term support of REAAWE throughout the design, production, and evaluation stages of BCI system development requires targeted efforts to reduce hardware costs and software complexity. Available solutions tend to have a small set of compatible systems, as well as project distribution support tied to proprietary backends (Neuromore 2022; Williams, McArthur, and Badcock 2020). Improved support for the dissemination of low-cost and/or open-source hardware can improve the chances that the technology needed to acquire real-time physiological data are available at home. Without affordable hardware, the viability of home BCISs remains minimal. Adoption of data standards could also reduce software complexity by increasing interoperability (Rübel et al. 2021; Gorgolewski et al. 2016). Development of novel BCISs informed by this principle might enable researchers to immediately deploy novel technologies to an active network of users who are empowered to provide suggestions and even directly contribute to further iterations.

In Spring 2020, Brains@Play produced the event Livewire: A Stimulating Night of Neurotechnology (USC Visions and Voices 2021). Forced to pivot due to the pandemic, we developed a web-based technology demo for online showcase. This enabled us to synchronously link an audience of two hundred fifty people with thirteen neuroscience, neuroethics, and interactive media experts. Such mass engagement results are a significant outcome of online events.

## 2.3 Strong Partnerships

Close collaboration with end-user populations could promote the uptake of novel home-use BCIs. Civil society organization partnerships can radically transform how research is perceived and executed for BCIs, leading to higher relevance and user acceptability (Stahl et al. 2017). Our team considers children with severe motor disabilities and their families as key partners in the translation of non-invasive BCISs. The need for accessible interfaces for adoption by families and caregivers could incentivize the usability of home-use systems. Technical innovations with child-inclusive features, such as advanced artifact rejection techniques that reduce electrical noise from fidgeting and uncontrollable muscle contractions, could broadly improve performance in naturalistic settings. Children with unaffected cognition are often excluded from experimental research. As a result, both the potential audience of BCI applications (BCIAs) and the incentive to design scalable systems in the first place remain limited (Bruno et al. 2009). Addressing limitations could help reduce the concern that BCIs are “essentially an orphan technology” with a market too small for uptake by industry (Wolpaw and Wolpaw 2012).

While efforts to engage pediatric patients in BCIR have already begun in Canada, further international involvement may advance such programs (Kinney-Lang et al. 2020). Beginning in 2021, Brains@Play helped produce the BCI Game Jam, an annual event where participants develop brain-controlled games for children with cerebral palsy (Kelly et al. 2020; BCI Games 2021). Our multiplayer BCISs supported several participating teams to distribute web games with multiplayer support.

## 2.4 Open Prototyping

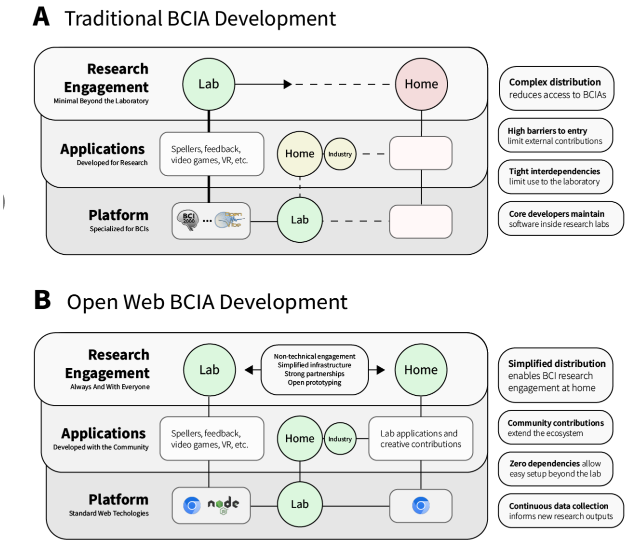
Active support of knowledge sharing between developers and end-users is essential for robust REAAWE in BCIs. Recent community-developed neuroscience software has strengthened the case for collaborative and open development practices (Vogelstein et al. 2018). Current research relies on the work of isolated academia and healthcare experts without unaffiliated community contributors' support. Established community members might instead train new members to practice skillful, user-centered work while communicating the rationale for community procedures and values (Gasson and Purcelle 2018). Engagement throughout development cycles could support contributing researchers, engineers, teachers, students, tinkerers, artists, and people with disabilities to critical science and health infrastructure throughout the translational science continuum (Gotsis and Jordan-Marsh 2018). Diversity and inclusion across demographics, disciplines, abilities, and methods may lead to accessible tools and impact quality of life for larger communities. A focus on building infrastructure *together* can create sustainable support for BCISs co-design.

The Brains@Play Platform was developed to showcase the latest developments in our software ecosystem and encourage rapid prototyping by our community (Brains@Play 2021b). Asynchronous engagement through GitHub, Discord, and Twitch helps to rapidly gather feedback about updates and inform development. Frequent appearances at student and professional hackathons have also contributed to community growth.

## 3 Leveraging the Open Web for BCIA Development

After its emergence in the early 1990s, the Open Web became the world's operating system, galvanizing a software industry composed of small development teams seeking to maximize impact via immediate, scalable software distribution. While the web browser was originally designed to view static documents, the underlying technologies have now evolved to support the implementation of serious applications without the installation and upgrade hassles of traditional software (Taivalsaari and Mikkonen 2017). This has made the browser environment an unparalleled platform for data visualization, exploration, and result-sharing.

These benefits have been recognized by the broader neuroscience community for some time. The Geppetto framework was developed to support web-based applications that visualize and simulate neuroscience data and models—including Open Source Brain, Virtual Fly Brain, NEURON-UI and NetPyNE-UI (Cantarelli et al. 2018). Over a decade of BCIR has leveraged web browsers as an interface for alternative communication and web browsing applications (Saboor et al. 2018; 2019; Mugler et al. 2010; Bensch et al. 2007; Martinez-Cagigal et al. 2017; Lin, Malik, and Zhang 2019; Placidi et al. 2016). BCI2000 was recently extended to allow research software to communicate with web applications (Milsap et al. 2019). Browser-based applications for real-time information filtering, authentication, meditation support, and internet-of-things have also been explored by HCI researchers (Orenda, Garg, and Garg 2017; Kumar, Bose, and Tripathi 2017; Hashiguchi et al. 2016; Peck, Afergan, and Jacob 2013). Since none of these research applications were designed to run standalone on a browser—making them no more accessible *in practice* than other software they rely on (e.g., BCI2000)—significant challenges to home-use scalability persist (Figure 1A).




**C** A Software Ecosystem for Open Web BCIAs

| Component | Purpose | Supporting Technologies | Proposals<br>See Supplementary Materials |
|---|---|---|---|
| **User Interface** | Rapidly distribute and extend BCIAs in the homes of end-users. | **Architecture**<br>Web Components<br>PWAs<br>**Graphics**<br>WebGL<br>WebGPU | visualscript |
| **Data Acquisition** | Gather real-time data from the browser. | Web Bluetooth<br>Web Serial<br>WebSocket<br>WebRTC | datastreams-api |
| **Data Management** | Store and reference data in a standard format. | **Standards**<br>Neurodata without Borders<br>Brain Imaging Data Structure<br>**Archives**<br>DANDI | webnwb<br>bids-standard |
| **Data Processing** | Implement high-performance computational pipelines. | Web Workers<br>WebGPU | hightime |
| **Networking** | Route acquired data to other remote or local processes. | HTTP<br>WebSocket<br>WebRTC | brainsatplay |

**Figure 1.** The potential benefits of BCIA development standards on the Open Web. (A) Traditional approaches to BCIA development are unidirectional with a lack of input from external contributors and end-users. (B) BCIA development on the Open Web enables Research Engagement Always And With Everyone via bidirectional input between core developers, public contributors, and end-users. (C) The initial specification of a software ecosystem that supports the rapid development of high-performance BCIAs on web browsers.

An emerging corpus of interdisciplinary work has successfully leveraged modern web technologies to create standalone BCISs on web browsers. Client-side JavaScript was benchmarked using the *bci.js* library for online processing of electroencephalography (EEG) data (Stegman, Crawford, and Gray 2018). EEGEdu was widely used by students to quickly interact with their own brainwaves (Mathewson, Mathewson, and Mathewson 2020). Block- and flow-based visual programming environments for the browser have also been evaluated to teach high-school students to construct BCIAs (Hernandez-Cuevas et al. 2020; Crawford and Gilbert 2019).

While existing literature proposes three architectural models for web-based BCISs—local, remote, and on-browser feature extraction—we argue that full investment in the browser as an open-source BCI workbench will simplify development workflows and offers the most benefits to end-users and engineers (Stegman et al. 2020). A common software ecosystem designed for modern web browsers could channel the work of academic, industry, and public contributors toward a common software ecosystem that supports home use by design (Figure 1B, C).

The following sections discuss the potential benefits of standardized software architecture for the rapid development of high-performance BCIAs on the Open Web.

## 3.1 Zero Dependencies

Standalone BCIAs for web browsers could simplify end-user experiences via free, ubiquitous access to innovations. While only the WebSocket API and HTTP requests were previously available to pass real-time data into the browser, the latest Chromium browsers have native Web Bluetooth and Web Serial APIs supporting direct real-time data acquisition from many commercial BCISs. Open-source libraries, such as *Webgazer.js,* have also been released by academic institutions to support behavioral tracking for psychological studies, HCI studies, and medical research, performing similarly to expensive hardware (Papoutsaki et al. 2016; Zhao, Lofi, and Hauff 2017).

Since the browser was originally intended to distribute documents, scientific communities have yet to broadly adopt web technologies for numerical computation of large datasets—though continued optimization efforts by browser manufacturers have enabled developers to write high-performance software without manual effort. Robust data processing needs are leading to the resurgence of "universal" or "isomorphic" application development in which the underlying JavaScript code can run both in the browser, server-side, and native application environments (Spike Brehm 2013). Additionally, the implementation of multithreading with Web Workers and GPU kernel processing has made it easier to build efficient, interoperable computational pipelines. Existing computational infrastructure across labs and private companies can remain supported through message-passing with a JavaScript server or the WebSocket protocol. Investment in such technology for BCI development could be an exemplary use-case that drives general innovation in the space of browser-based high-performance computing.

## 3.2 Simplified Distribution

The distributive benefits of the Open Web have been fundamental to its success, enabling the continuous deployment of web-hosted resources to users around the world. Modern development practices allow websites to be designed as Progressive Web Applications that allow end-users to install the page on desktop and mobile devices for a native-like experience that is reliable without internet access (Mole 2020). With the growing popularity of Chromium browsers, a standard browser architecture could emerge with guaranteed access to the latest APIs. Development of standard JavaScript libraries for common experimental, training, and assistive paradigms (e.g., grid selection, etc.) in BCIs could be useful for supporting research technology transfer on the Open Web. Standards integrated into Web Components (reusable custom elements with encapsulated functionality), which were missing and historically limited code reuse at the user interface, can further simplify developer integration (Taivalsaari et al. 2017).

## 3.3 Continuous Data Collection

Broad engagement of stakeholders in BCIR at home could allow massive automatic data sharing with web-based research programs. Continuous and ubiquitous data management and sharing practices integrated early into the BCIR pipeline could practically and ethically handle this data influx (Dempsey et al. 2022). Informed consent can learn from similar investigations into personal neurological data and protocols enabling sharing of de-identified genomics data. Automated raw data organization into standardized data formats and publication on data archives could be developed for process streamlining (Rübel et al. 2021; DANDI Archive 2022; Gorgolewski et al. 2016). Pairing this with integrated data sharing could make open datasets an expected research output for future studies. Robust open governance models, interoperable data infrastructures, and individual commitment to reproducible and FAIR research practices are likely to help support the success of standardization efforts as accepted standards change and evolve (Poline et al. 2022). Expanded mandates on data sharing by funding agencies and publishers can drive innovations in this direction.

## 3.4 Community Contributions

With JavaScript as the foundational Web programming language, over sixteen million developers—more than any other language—could contribute to the browser-based BCI software ecosystem (SlashData 2021). The adoption of modular development practices would enable low-effort contributions through the abstraction of complex computational processes that can both integrate and be integrated into other codebases. Support for non-native networking protocols such as Open Sound Control (OSC) and Lab Streaming Layer could also support integration into existing scientific and artistic workflows that exist off the browser. Previous developments in translational computer science, such as the emergence of grid computing, are useful models for the successful rollout of computational infrastructure for BCIR on the Open Web—especially commitment to sustained development, maintenance, and enhancement of software (Foster and Kesselman 2004; 2021).

## 4 Conclusion

Broad REAAWE integration could be transformative for the practice of BCIR, allowing the field to deliver on its promises to people with disabilities by distributing the latest innovations directly into the home. Shifting development to the Open Web would also dramatically lower the barrier of entry to BCIS development for people without strong technical backgrounds—allowing for a co-developer community to flourish around the latest research. Widespread adoption of this approach is likely to remain limited in the absence of exemplary work within the field, formal support by funding institutions and Ph.D. programs, and incentives provided to end-users and public contributors (Abramson & Parashar, 2019). While we proposed the initial specification of a BCI software ecosystem on the Open Web, ongoing collaboration between researchers and end-users will be required to settle on a community standard that minimizes impact on existing workflows and can be met with distinct implementations. Further collaborative research with HCI researchers could uncover best practices for engaging BCI end-users across clinical and community settings. Anyone interested in broadening participation in BCI development should reference our organization's GitHub repository aligned with the specification presented in this paper (see Supplementary Material).

## 5 Conflict of Interest

The authors disclose their role as founders of The Brains@Play Initiative (now Brains@Play, LLC) at the University of Southern California. In-kind support has also been provided by BCI Games, OpenBCI, PLUX Biosignals, Enosis, NeuroTechX, USC Games, the USC Media Arts and Practice Division, and the USC SMART-VR Center.

## 6 Author Contributions

GF wrote the manuscript with support from JB, MG, and DS. All authors contributed sections to the article, edited and approved the submitted version.

## 7 Funding

This study was partially funded by NIH 3RF1MH117800 subaward to DS and a USC Annenberg Graduate Fellows Micro Seminar Series Research Grant awarded to DS, MG, and GF. The projects discussed in this paper related to Brains@Play were funded by the USC Arts & Humanities Initiative for the 2020-2021 Visions and Voices event series and the USC Bridge Art and Science Alliance.

## 8 Acknowledgments

The work of Brains@Play could not continue without the support of our community of collaborators and stakeholders in the future of BCI use at home. A list of past and present contributors to our research engagement activities can be found at https://brainsatplay.com/about.

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## 10 Supplementary Material

The source code associated with this publication is released under the Affero General Public License (AGPL) at https://github.com/brainsatplay.