NeuroCHI: Are We Prepared for the Integration of the Brain with Computing?

Yudai Tanaka*
University of Chicago
Chicago, Illinois, USA
yudaitanaka@uchicago.edu

Angela Vujic*
MIT Media Lab
Cambridge, MA, USA
avujic@mit.edu

Pattie Maes
MIT Media Lab
Cambridge, MA, USA
pattie@media.mit.edu

Robert J.K. Jacob
Tufts University
Medford, MA, USA
jacob@cs.tufts.edu

Olaf Blanke
Swiss Federal Institute of Technology (EPFL)
Geneva, Switzerland
olaf.blanke@epfl.ch

Sho Nakagome
Reality Labs Research, Meta
Redmond, WA, USA
snakagome@meta.com

Pedro Lopes
University of Chicago
Chicago, Illinois, USA
pedrolopes@uchicago.edu

ABSTRACT

Recent advancements in neuroscience, wearable technology, and artificial intelligence are paving the way for computing systems that are integrated with the brain and nervous system. Over the past years, we have witnessed the simultaneous progression of wearable neurotechnology and AI-based modeling and analysis of brain data. Coincidentally, this period has also seen HCI researchers showcase their translational work, incorporating neuroscience insights into innovative interactive systems, including brain-computer interfaces (BCIs) and non-invasive brain stimulation. These efforts may transform our brain and nervous system activity into direct interfaces for interacting with computing systems. Our panel poses the question: "Is the HCI community ready for the integration of the brain with computing?" Together with a panel of experts, we will review the current state of the intersection between HCI and neurotechnology, discuss the research questions and novel applications that emerge from merging these two fields, and debate ethical implications.

CCS CONCEPTS

• **Human-centered computing** → **Human computer interaction (HCI)**; • **Hardware** → *Emerging technologies.*

KEYWORDS

Neurotechnology, Brain-Computer Interface (BCI), Neurofeedback, Physiological Computing, Transcranial Magnetic Stimulation, Electrical Muscle Stimulation

*These authors contributed equally and are ordered alphabetically.

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1 INTRODUCTION

Over recent years, innovations in neurotechnology have expanded beyond laboratory settings, enabling advancements like mobile brain sensing through high-fidelity electroencephalography (EEG) and the practical application of brain-stimulation interfaces in prosthetics [10]. Additionally, acting as a catalyst, there has been a surge in compact and affordable commercial neurotechnology (e.g., EEG headbands from Muse [25], fNIRS eyeglasses from BlueberryX [1] and EMG wristbands from Meta [4]), alongside research advancements in AI-based brain data decoding of semantic information [38]. These consumer neurotechnologies can eventually enable continuous long-term brain-computer interfacing with a broader demographic of users that creates large datasets. In turn, larger data sets enable AI models that can detect patterns and anomalies not possible with traditional methods. Last, large language models (LLMs) may provide an interface to help users make sense of a large corpus of data, and provide instantly generated insights and recommendations. These progressions are not only accelerating our understanding of the brain but also opening up new possibilities in HCI, paving the way for computing systems that are integrated with the brain.

Coincidentally, this period has also seen HCI researchers showcase translational work that incorporates neuroscience insights into innovative interactive systems. These works include interactive systems built on directly decoding brain signals [12, 18, 32, 48]. Or even, outputting sensory information by intercepting the peripheral nerves [15, 21, 33, 36], as well as non-invasive brain stimulation [31, 35].

We believe that these developments may indeed move brain-computer interfacing from speculative exploration to an HCI reality, leading us to pose the question: "How is the HCI community preparing for this?". Together with a panel of experts, we initiate the step towards nurturing the HCI field that intersects with neuroscience, which we call NeuroCHI. NeuroCHI is a portmanteau of "neuroscience" and the Computer Human Interaction (CHI) acronym meant to signify a subfield of HCI involved with the use of brain and nervous system input and/or stimulation in the study of HCI or as the interaction method of an interface. We will recap the current state of NeuroCHI, discussing novel techniques and applications, as well as articulating technical challenges and ethical implications.

2 BACKGROUND

2.1 Decoding the Brain and Nervous System

For over two decades, the idea of using brain input in HCI has steadily grown. HCI brain-input research has focused on non-invasive techniques, particularly EEG and functional near infrared-spectroscopy (fNIRS). Solovey identified the first mention of brain input in HCI literature as being Velichkovsky and Hansen in 1996 [32], who broadly described how non-invasive brain imaging could be applied to HCI research [40]. In 2001, Doherty et al. presented design recommendations for creating assistive EEG-BCIs for yes/no communication [8]. Later, Lee and Tan presented "Using a Low-Cost Electroencephalograph for Task Classification in HCI Research" at UIST 2006, which helped pave the way for non-clinical BCI research in HCI. [18, 32].

BCI in HCI has included interfaces where brain input is a primary interaction method as well as brain input as a method of studying HCI systems. Applications have spanned attention management [12, 16], meditation techniques [2, 47], tailored learning experiences [48], interactive gaming [5, 9], assistive technologies [8] and the emerging field of emotion modulation [43]. Using BCI to study HCI systems has included using low-cost EEG to track error-related negativity for design-related tasks [41], related to Lee and Tan's early work in task classification.

In comparison with EEG, fNIRS is more robust to movement artifacts, which improves its usability in HCI applications. fNIRS has been used with success to gauge cognitive load, enabling systems to adapt dynamically [32, 39, 48]. "Learn Piano with BACh" [48] demonstrated how adjusting the difficulty of musical lessons based on cognitive workload could improve accuracy and speed in piano learning. Brainput [32], a dual-robot-control BCI system, showed how performance and subjective task load index scores could be improved through fNIRS input.

EEG in contrast with fNIRS offers the advantage of being lower-cost and much easier to integrate into wearable technologies. This advantage has enabled socially acceptable form factors, either disguising brain imaging technologies as more common objects or creating slim, minimally obtrusive wearables. The AttentivU device [16], for instance, incorporates EEG sensors into eyeglass frames, providing real-time feedback on attention levels, fatigue and more. Interaxon's Muse headset [25] offers neurofeedback for meditation through an EEG headband. Neurable's headphones [26] include around-ear EEG sensors, monitoring brain signals for performance feedback. Additionally, OpenBCI's Galea [5] merges EEG with virtual reality (VR) technology. The convenient form factors of these EEG devices could enable real-world data collection at mass-scale that is compatible with advancements in AI that require large datasets.

2.2 Stimulating Nerves & the Brain

While the human sensory system is designed to receive information through end receptors such as eyes, ears, and skin, enabling audiovisual and tactile sensations, it is also possible to bypass these receptors by directly intervening in the nerve pathways or even at the source (i.e., the brain). This approach is particularly crucial for aiding individuals with disabilities affecting these end receptors [34], as well as for understanding the functions of the nervous system [28].

Over the past decade, researchers have developed interactive systems based on these stimulation principles, exploring their interactive benefits. These efforts include providing force feedback by moving users' limbs through electrical muscle stimulation (EMS) [21]. Another innovation involves delivering touch sensations to the user's hand or fingerpad without attaching devices directly to these areas; instead, stimulation is applied to different body locations, such as the back of the hand [36] or wrist [24]. Furthermore, a notable exploration is rendering the sense of whole-body movement and acceleration in immersive experiences by stimulating the vestibular system (GVS), as opposed to using motion platforms [33].

These works have demonstrated the advantage of actuating the user's sensory system without impeding their body with bulky hardware devices, which is a driving force in HCI. Considering that electrochemical signals processed through neurons form the basis of our perception and actions, these approaches directly induce such reactions via electrical stimuli applied to the nervous system, thereby eliminating the need for bulky hardware components (e.g., motors) that would otherwise be necessary.

Beyond stimulating peripheral nerves, the logical progression toward more centralized sensory intervention involves direct stimulation of the spinal cord and brain—the sources of the nervous system. Stimulating the spinal cord has been extensively explored in the realm of rehabilitation [14]; however, its application in interactive systems remains rare. Recently, Jain et al. demonstrated that a cold thermal stimulus applied to the spinal cord can enhance users' emotional response to aesthetic chills (i.e., goosebumps, psychogenic shivers) [15].

Although still relatively nascent, there has also been exploration into non-invasive brain stimulation for creating interactive experiences. For instance, researchers have enhanced illusions of tactile perception [31], VR locomotion [17], or induced visual phosphenes [7] through stimulation applied via electrodes attached to the scalp (tCS). While tCS allows for modulating perception, it typically lacks the accuracy to generate sensory feedback by itself. In contrast, non-invasive magnetic brain stimulation, i.e., transcranial magnetic stimulation (TMS) can directly and instantly excite neurons in cortex. When this is applied to the sensorimotor cortex, it can induce tactile sensations and limb movement [11]. Recently, Tanaka et al. demonstrated that TMS is even able to provide interactive haptic feedback across the user's whole body (e.g., hands & feet) by stimulating different parts of the sensorimotor cortex [35].

2.3 Next Steps for NeuroCHI

While novel and promising, NeuroCHI is faced with practical and ethical challenges. Signal quality varies widely between individual users and also between sessions for the same user. Noise artifacts are frequent and often signal-to-noise ratio (SNR) is low when compared with other types of physiological, non-contact, etc. techniques. EEG-BCIs have electromagnetic artifacts as well as motion artifacts. fNIRS-BCIs are more resilient to motion artifacts, but contain light-based artifacts and have a slower response time. In stimulation techniques, sensor precision is steadily improving, actuator precision lags behind, particularly evident in real-world user assistance applications. For example, electrical muscle stimulation (EMS) shows promise in compact force-feedback for wearable technology, but it faces significant limitations, such as imprecision in facilitating fine movements and discomfort due to the tingling sensation it generates [37].

For a long time, neurotechnologies were considered too bulky and expensive to be used outside of the laboratory environment. In recent years, researchers and companies have been able to develop wearable form factors, such as headphones, eyeglasses, "earables", and more [6, 27, 29, 42]. With the possibility of continuous, long-term monitoring or stimulation of neural signals, AI could be applied to perform novel pattern and anomaly detection which was not previously possible. This could open up new applications of neurotechnologies for HCI researchers and end-users. However, this brings up a host of new questions, also aput forth by Wilson et al. [46]: what will be the primary goal of tracking cognitive activity? Is there an ideal level of cognitive activity? How will these interfaces ultimately benefit the end user? AI and commercial developments will no doubt create changes in the area of practical challenges, as interfaces with the capability to "read" images and semantic information directly from brain signals emerge.

Ethics. The capability of accessing and influencing users' physiological states through technology brings ethical challenges concerning privacy, consent, data security, and the morality of influencing user states [49]. These aspects can be controlled in laboratory studies, where protocols can strictly adhere to user consent, user screening, and established parameters that ensure users' agency and safety [30]. However, it becomes significantly more challenging to ensure these aspects when neurotechnologies are scaled up for consumer deployment. Moreover, there is no unified, global, mechanistic explanation of brain function currently existing in neuroscience. This limitation means that we are unable to fundamentally understand the full impact of NeuroCHI technologies that we create, and raise the question of how and whether they should be pursued. The limited understanding of brain function also leads to ethical concerns of the marketing and distribution of consumer neurotechnologies; these often lack scientific evidence for their safety and efficacy, making improvements in regulatory oversight crucial [44]. Neurotechnologies can impact feelings of agency, create false sense of self, be used for attention and addiction highjacking, further worsen inequality and reinforce preexisting biases, cause discrimination, and even influence arms races [49]. A proactive understanding and examination of these issues is crucial for the responsible and ethical progression of the field.

3 PANEL FORMAT

The panel includes **four panelists and two moderators**. It will be **hybrid** i.e., the panel will be held in person, with the option for attendees to also participate virtually. The panel will start with the moderators introducing the panelists and the discussion topic. Each panelist will have two minutes to summarize their research and perspectives on NeuroCHI. The moderators will then highlight the rise of neuroscience-rooted interactive systems in HCI, leading into a speculation on NeuroCHI's future, including technical challenges and ethical implications. This will form the bulk of the session. The moderators will use the following prompts to guide the discussion, while also encouraging audience interaction.

- What are the emerging hot topics and application domains in NeuroCHI?
- What are the ethical implications of using brain signals and stimulation interfaces?
- Beyond input decoding and haptics, what are the breakthrough applications of NeuroCHI?
- What are the key challenges and potential game-changers for the sensing aspect?
- What are the key challenges and potential game-changers for the stimulation aspect?
- What role can HCI researchers play in fostering innovations in neurotechnologies?
- Is society ready for the further deployment of BCI/stimulation interfaces? If not, what is missing?

After the introductions (15 minutes) and initial discussion (30 minutes), we will open the floor for a discussion with the audience. We encourage an interactive debate and deep discussion around these questions, considering the timely and controversial nature of the topic. To ensure efficient time management, each panelist will be allotted a maximum of 3 minutes to speak during their responses. Remote attendees can ask questions through either the chat function or a question-submission portal.

Relevance to the CHI community: The CHI community has shown growing interest in interdisciplinary research linking neuroscience with HCI. At CHI 2022, for instance, Wilson, Midha, Maior et al. presented a cognitive informatics special interest group (SIG), fostering collaboration among researchers in personal informatics, digital health, neuroergonomics, and neuroethics [46]. Earlier, at CHI 2018, Nijholt, Jacob, Andujar, Yuksel, and Leslie led a workshop focused on non-clinical HCI and BCI research [23]. Our panel seeks to build upon these previous efforts, continuing this vital conversation. Moreover, some of our organizers (Prof. Lopes and Prof. Maes) previously co-led a relevant SIG at CHI 2021, connecting HCI researchers in physiological sensing and actuation techniques [20].

Logistical needs, audience engagement & hybrid requirements: Our logistical requirements are straightforward, encompassing standard audio/visual support suitable for a hybrid event. To engage our audience, we will collect real-time questions using the Slido platform. We prefer to have a projector to display introductory slides and, later, the audience's Slido questions. For remote participation, a camera setup for Zoom streaming is essential. Alternatively, a student volunteer could stream the event using their personal device. We also require an additional student volunteer to assist with microphone distribution for in-person audience queries, particularly for follow-up questions not submitted via Slido.

4 PANELISTS

The panel is organized by two Ph.D. students, **Angela Vujic** (MIT Media Lab) and **Yudai Tanaka** (The University of Chicago), along with their advisors, **Pattie Maes** (Professor at MIT Media Lab) and **Pedro Lopes** (Associate Professor at The University of Chicago). Angela's doctoral research focuses on interdisciplinary transfer of neuroscientific models and theories to develop novel brain-computer interface techniques in HCI. Yudai's doctoral research focuses on the development of haptic actuators based on neurological principles such as surface-electrical stimulation and non-invasive brain stimulation. Angela and Yudai also serve as moderators.

To provide a complementary perspective on the topic, we invited leading experts from both academia and industry, who are specialized in the field of BCI technology, somatosensory and cognitive neuroscience, as well as HCI systems leveraging neurological principles—both input and output.

Pattie Maes (in-person attendance) is the Germeshausen Professor of Media Arts and Sciences at MIT Media Lab and a faculty member in MIT's Center for Neuro-Biological Engineering. She directs the Fluid Interfaces group, where she investigates the topic of cognitive enhancement, or how wearables and brain-computer interface systems can actively assist people with issues such as memory, attention, learning, decision-making, communication, well-being, and sleep. Research from her Fluid Interfaces team includes affective BCIs such as joy-based BCI [43], neurotechnologies for enhancing creativity, memory and wellbeing through sleep [13, 45], wearable BCI for attention [16], and stimulation technologies such as vestibular stimulation to aid motion sickness in VR and spine stimulation to simulate chills [15, 33] *Website: www.media.mit.edu/groups/fluid-interfaces*

Robert J.K. Jacob (in-person attendance) is a Professor of Computer Science at Tufts University, where his research interests are new interaction modes and techniques and user interface software; his current work focuses on implicit brain-computer interfaces. Over the past decade, his research group has been developing real-time, implicit Brain–Computer Interfaces (BCIs) using functional near-infrared spectroscopy (fNIRS), including Learn Piano with BACh which was awarded best paper at CHI 2016 [48]. He received his Ph.D. from Johns Hopkins University, and he is a member of the editorial board for the journal Human-Computer Interaction and a founding member for ACM Transactions on Computer-Human Interaction. He has served as Vice-President of ACM SIGCHI, Papers Co-Chair of the CHI and UIST conferences, and General Co-Chair of UIST and TEI. He was elected as a member of the ACM CHI Academy in 2007 and as an ACM Fellow in 2016. *Website: https://www.cs.tufts.edu/ jacob/*

Olaf Blanke (virtual attendance) is a Professor and holds the Bertarelli Foundation Chair in Cognitive Neuroprosthetics at the École Polytechnique Fédérale de Lausanne (EPFL), where he directs the Laboratory of Cognitive Neuroscience. Blanke's research fosters a neuroscientific understanding of multisensory bodily perception and self-consciousness, leveraging technologies such as virtual reality (VR), mixed reality (MR), and haptics, alongside traditional neuroscience experimental methods. He is particularly renowned for his work on inducing out-of-body experiences through a visuo-haptic illusion in VR [19]. His research group also pioneers foundational research in neurological stimulation techniques, including galvanic vestibular stimulation (GVS) [22] and transcranial magnetic stimulation (TMS) [11]. *Website: www.epfl.ch/labs/lnco*

Sho Nakagome (in-person attendance) is a Research Scientist at Meta Reality Labs, initially worked on Brain Computer Interface (BCI), and now on HCI. Sho and the team published a paper on a novel portable diffuse optical tomography (DOT) [3], concluding the work on BCI at the company. Now focusing on HCI, Sho's interests reside in multi modal inputs and use of various biosignals, increasing decoding and encoding of information between human and computer to build new applications. Sho received his Ph.D. in Neural Engineering from the Non-Invasive Brain Machine Interface Lab at the University of Houston, where he specialized in development for EEG-based gait decoding.

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