ABSTRACT BOOK

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10th International BCI Meeting

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Natalie Mrachacz-Kersting, Jennifer Collinger, Donatella Mattia, Davide Valeriani, Mariska Vansteensel, Gernot Müller-Putz

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10th International BCI Meeting

Balancing Innovation and Translation

The International Brain-Computer Interface (BCI) Meeting Series is one of the primary forums for exchanging fundamental information between all subdisciplines in the field of Brain-Computer Interfaces. It is the flagship meeting for the Society of Brain-Computer Interfaces founded on March 13, 2015. Neurologists, neuroscientists, computer scientists, rehabilitation engineers, physicians, therapists, engineers, psychologists, pathologists, ethicists, and actual BCI users are all active participants in the BCI Meeting Series. The 10th International BCI meeting will focus on the important and timely topics centered around ***balancing innovation and translation*** in the field of BCI.

Posters and presentations cover research within basic, translational and clinical applications as related to BCIs. The diversity of applications for which BCIs are developed, and the diversity of data and analyses that contribute to progress BCI research, are reflected in the abstracts contained within these Proceedings. It is clear that innovation continues to be a main driving force behind BCI developments, though in recent years the number of BCIs that have been translated to real-world applications has steadily grown. This is exemplified by the numerous clinical trials that have explored the efficacy of BCIs for replacement, restoration and enhancement of function.

We are very excited that this balance between innovation and translation is reflected by our three distinguished colleagues that have accepted our invitation as keynote speakers. Edward Chang, Professor of Neurological Surgery at the University of California, San Francisco, Andrea Kübler, Biologist and Psychologist and Associate Professor at the University of Würzburg and Tomas Oxley, Associate Professor from the University of Melbourne, Australia and founding CEO of Synchron, a brain data transfer company.

On behalf of the BCI Society and the Program Committee for the 2023 BCI meeting, I thank you for your interest in the BCI Meeting and look forward to meeting you at this as well as future installments in the BCI Meeting Series.

Natalie Mrachacz-Kersting, PhD
University of Freiburg, Germany
Scientific Program Committee Chair

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Lead Reviewer - **Category**

Erik Aarnoutse - BCI implant control
Peter Brunner - BCI implant – other
Cuntai Guan - Signal analysis
Gernot Müller-Putz - BCI non-implanted
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Aleksandra Vuckovic - Signal acquisition

E-Book preparation

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Real-Time Mobile Robot Obstacles Detection and Avoidance Through EEG Signals

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***Abstract*—Human-Machine Interface (HMI) and Brain-Computer Interface (BCI) have recently emerged as an efficient solution for many machine controlling or computer application in order to send direct controls' commands or provide feedback to correct some robot actions during task execution [1], [2], [3]. However, there are many challenges for designing an efficient and effective BCI system that requires less mental effort involving humans brain, so that it could be a practical tool for daily-task without to request extra brain effort. In the related works, Electroencephalographic (EEG) signals, acquired by external electrodes placed on the human scalp, are used as input for the implemented algorithms to correct possible faults and errors during the robot's task performance [4], [5]. Although there are many works focused on the use of BCI with the goal of real-time feedback based on EEG signals detection, the idea of using them as input to algorithms in order to correct possible faults and errors during the robotic task, as in the proposed case of obstacle avoidance during navigation of this paper, still remains a challenging goal [6]. In addition, most existing BCI protocols for involving humans in the robot control's loop, require the user observes a full visual and brain concentration in order to have good signals for different cognitive situations [1].**

The aim of this study is to design a BCI-based protocol to be used with a wheelchair-robot control system for safe navigation in an indoor scenario, that can avoid obstacles not detected by the on-board sensor equipment. Moreover, the design of a specific protocol has the aim of evoking and collecting EEG data for training and testing the BCI system which will be integrated with ROS (Robotics Operation System). In ROS environment, the BCI will be lined with a package, already developed [7]–[9], that generates virtual obstacles and supports the human in the loop approach integration. The designed protocol has been implemented by using a simulation platform (i.e., Gazebo), including both an environment and a specific mobile robot, namely a smart wheelchair. The smart wheelchair can navigate autonomously in the indoor scenario, avoiding possible obstacles without any human intervention using only the available sensors that equip the smart wheelchair. However, in the case that the sensors can fail in the obstacle detection, due to occlusions or unexpected obstacle positions, the involvement of human in the robot path planning control improves the human safety. During the training phase with the BCI system, the user is asked to observe a video during which the robot is trying to avoid the obstacles (i.e., holes positioned in the floor), placed along the path, particularly focusing when the smart wheelchair fails the task (e.g., runs into a hole in the floor). According to the well-known "oddball paradigm" [10], used to elicit the P300 ERP (Event-Related Potential), a sequence of events, that can be classified into two categories, is presented to the subject at a very fast rate. In general, events of one category, that can be considered as "target stimuli", must have a lower frequency of occurrence with respect to the other. By engaging the subject in a cognitive task, for example by instructing him/her to progressively and mentally count the number of times the target stimulus appears, the P300 is generated. In this way, presenting to the subject the smart wheelchair that passes through the obstacle or turns around it, the user's brain is expected to generate particular EEG signals, namely the ERPs. These EEG signals will be recorded and sent to the BCI system that processes them and classifies the event. The recognized ERPs are then used as input signals for a developed Matlab-Simulink algorithm. In particular, the Simulink file runs a node that publishes a trigger topic, through cloud service, for the robot, in a ROS-based architecture that integrates the robot navigation packages with the signal recognition provided by the BCI system. The data have been collected from 10 healthy subjects, and each of them performed 150 trials, in 25 minutes. This data is then divided for training and testing phases. The data has been processed in a Matlab environment, basically in EEGLAB and BCILAB. EEGLAB has been used to process all data off-line in order to investigate all the neurophysiology properties (i.e., signal shape and potential activation zones), which will be better optimized for the classification, among them the best channel and the optimum frequency bandwidth for the interesting events. Instead, the BCILAB has been used for all event classification and reprocessing online and offline. The pre-processing step has been tuned based on the results obtained from EEGLAB. The paradigm with the best classifications accuracy and fewer computation efforts has been used for the online integration with ROS. The overall results show that the area under the curve for training and testing respectively are 0.73 and 0.59, while the standard deviation for training and testing are 0.11 and 0.07 respectively. Different simulation results will be presented in the extended version of this work.

In conclusion, this study shows the possibility of using human brain signals, recorded through a BCI system, in order to provide a real-time human-in-the-loop approach for monitoring

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the reliability of a robot while executing the obstacle avoidance task. The obtained results show that the proposed solution can significantly improve safety conditions during human-robot interaction, providing feedback accordingly.

Index Terms—**Human-in-the-loop, BCI system, ERP detection,EEG Brain Robot interface, Obstacle avoidance, Robot navigation.**

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EEG Biomarkers of Working Memory, Attention, and Fatigue

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Introduction: In this study, we evaluate the effectiveness of different workload biomarkers under distinct experimental conditions to assess their suitability in different application areas. We have worked with EEG data from three open datasets: 1) Subjects (N=14) in a short-term memory task [1]; subjects (N=36) during two different conditions: resting state and arithmetic operation performance [2]; subjects (N=27) while performing a 90-minute Virtual Reality (VR) driving task [3].

Material, Methods, and Results: A frequency-band power analysis was performed. Results showed significant increases in the theta-to-alpha ratio (TAR) with increasing cognitive demands and increased slow-to-fast ratio (SFR) at temporal areas under fatigue (see Figure 1).

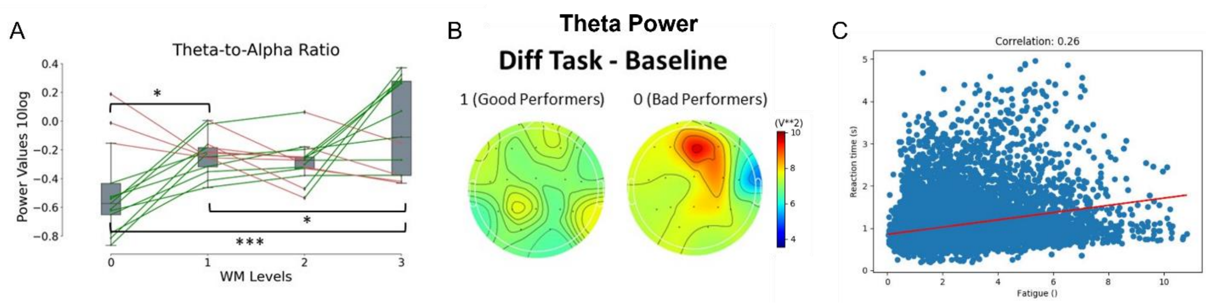

***Figure 1**. **A.** Theta-to-Alpha Ratio computed for the EEGLearn data set [1]. Significant increases were found in response to increasing cognitive demands. **B.** Theta power topographic activity during a mental arithmetic task [2]. Bad performers showed larger values of midfrontal theta than good performers. **C.** Slow-to-fast power ratio computed at temporal electrodes during a driving task [3]: Correlation (R = 0.26, p < 0.0001) between the slow-to-fast ratio computed five seconds before lane deviation and participants' reaction time for correction.*

Discussion: We validated the theta-to-alpha ratio as a reliable working memory biomarker both during memory and mental arithmetic conditions [1,2]. Furthermore, this indicator can help to distinguish, even at the individual level, the amount of cognitive effort that a certain user needs for a particular task. In addition, we found the SFR to be a good indicator of the fatigue and alertness levels of the users in [3].

Significance: We have found evidence for using working memory, attention, and fatigue EEG markers that are flexible enough for a wide range of applications and will play an essential role in the future of passive BCI. Especially applications in Virtual Reality, User eXperience Assessment (UXA), and Ergonomics can benefit from such markers for the objective characterization of user response and performance.

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An EEG Source Imaging BCI for Movement Decoding in Youth with Brain Lesions

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Introduction: Traditional brain-computer interfaces (BCIs) based on electroencephalography (EEG) typically make no accommodations for users with brain lesions. EEG source imaging (ESI) is a neuroimaging technique to estimate cortical potentials based on scalp EEG signals [1]. By constructing anatomical models of the head using magnetic resonance imaging (MRI), ESI may help compensate for variability in head tissue morphology and cortical geometry in BCI users, potentially improving classification performance [2-5]. For this reason, we investigated the feasibility of an ESI BCI for classifying hand movement and imagery tasks in youth with brain lesions.

Material Methods and Results: T1-, T2-, and diffusion-weighted anatomical MRI scans were acquired from 9 pediatric participants (16 ± 2.5 years old) with brain lesions. Subsequently, EEG activity from 64 channels were recorded with a Brain Products actiCAP wet system while each participant completed hand movement and imagery tasks over two sessions. The anatomical MRI images were used to segment the head into different tissue types including white matter, gray matter, cerebrospinal fluid, skull, and scalp. The conductivity characteristics for each tissue type were used to construct a volume conduction model that describes how electrical signals propagate through different brain regions. The resulting model was used to compute a lead field matrix that projects the scalp EEG signals into approximately 1000 cortical sources located over an evenly distributed grid sampled over the cortex with 10 mm resolution. The EEG signals were pre-processed and spatially co-registered with the MRI before time-frequency features were extracted for the classification of left versus right-hand motor execution and imagery tasks. The classification performance of the scalp EEG approach was compared to that of the ESI approach. Generally, the classification accuracies of ESI BCIs were comparable to those of corresponding EEG BCIs. When compared to the EEG BCI, the ESI approach showed an improvement of 8.68±7.84% ($p < 0.001$) in one participant for the motor execution task and 10.91±16.85% ($p < 0.05$) in another participant for the motor imagery task.

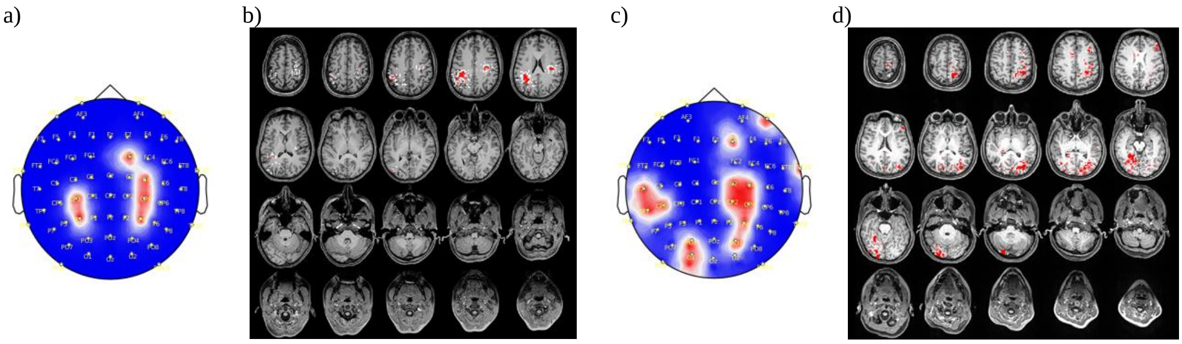

Figure 1: Topographical maps for participants and tasks with the maximum improvement in classification accuracy for the ESI BCI; a) and b) present the EEG scalp maps and ESI source distribution maps for the hand movement task; c) and d) present the EEG scalp maps and ESI source distribution maps for the hand imagery task

Discussion: Overall, ESI shows potential in improving the classification performance of BCIs. However, substantial research is still needed to validate its feasibility in a larger population of users with different brain lesion types and locations, motor ability, and age. In addition, given that the MRI is needed for anatomical modeling, ESI BCIs need to substantially improve over EEG BCIs in decoding multiple complex tasks to justify the associated costs in practice. Finally, considering the additional computational cost required for ESI processing, future research would also need to demonstrate the feasibility of ESI BCIs for users with brain lesions in an online setting outside of the laboratory setting.

Significance: To the author's knowledge, this is the first study to investigate the feasibility of an ESI BCI for decoding motor execution and imagery tasks in youth with brain lesions.

Acknowledgements: This work was supported in part by the NSERC CGS-M grant.

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Recruiting Neural Field Theory for Motor Imagery Data Augmentation

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Introduction:

Brain-computer interfaces (BCIs) allow for controlling computer and robotic applications directly with brain activity. A common problem in BCI systems is poor classification accuracy due to a lack of diverse training data, which is typically collected during exhausting calibration sessions. A possible solution to increase the amount of training data is augmenting them with a computational model of neural dynamics. Here, we focus on Neural Field Theory (NFT), a powerful technique for constructing physiologically-inspired models of large-scale brain activity. These models can be fitted to experimental EEG spectra and generate artificial EEG time series accordingly [1].

Materials, Methods and Results:

We fitted NFT models to common spatial patterns (CSP) of each MI class, jittered the fitted parameters, and augmented trials by generating CSP signals from the models. We computed the total power (TP) of the CSPs as well as their Higuchi Fractal Dimension (HDF) and applied Linear discriminant analysis (LDA) to classify MI states based on these features. We used the "2a" dataset from BCI competition IV to test the accuracy improvement. To imitate a small training set, we randomly split the dataset into 3 equal folds and used the first fold for training and NFT augmentation, and the other 2 folds for validation (see Figure 1). Using the TP feature, we reached a classification accuracy of κ=0.82 (Cohen's Kappa) for the full training set, κ=0.79 for the small training set, and κ=0.83 for the augmented training set. In comparison, an augmentation that was based on adding Gaussian noise to the features yielded κ=0.76 for the augmented training set. HDF feature didn't present an improvement in accuracy.

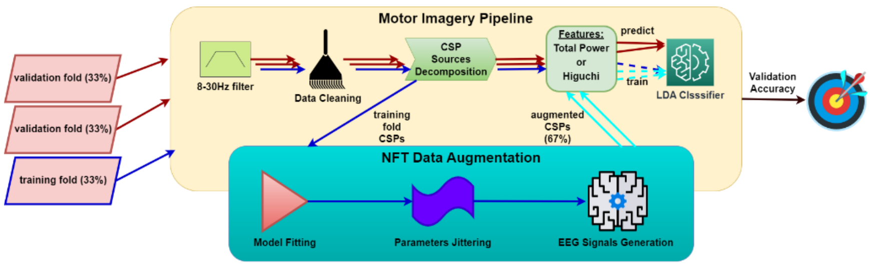

Figure 1: Data augmentation experiment flow

Discussion:

NFT-based data augmentation successfully improved classification accuracy to the level of a full training set. It performed much better than noise-based augmentation suggesting that NFT generates a signal with a more realistic distribution. The improvement was present for TP-based classification but not for HFD-based, implying that NFT generates EEG signals that better encompass spectrum-based features rather than time-domain-based features.

Significance:

Our findings demonstrate that data augmentation using a physiological model (here NFT) can improve the accuracy of BCI classifiers when the number of training samples is limited. This approach provides biophysical meaning to the generated signals and can improve accuracy to the level of a large, diverse training set.

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Individuals with neurodegenerative disease discuss values about the speed-accuracy trade-off in communication BCIs

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Introduction: Messaging with communication BCIs is not as accurate or fast as spoken language. The slow rate or inaccurate word choices might be a barrier to adoption, especially by potential end-users with neurodegenerative disease who have been competent communicators their entire lives. Understanding how potential end-users conceptualize this trade-off, what they would accept, why, and in what contexts, is critical for designing devices that meet end-users' needs and preferences. This study, which is part of a larger research agenda on ethics and BCI communication [1], examined the values that potential end-users ascribed to the speed-accuracy trade-off that must be considered during device development, training, and usage.

Methods and Results: Sixty-six individuals with neurodegenerative disease responded to prompts about six hypothetical ethical vignettes. Eight participants used augmentative and alternative communication devices for expression, and the remaining 58 were natural speakers, experiencing different degrees of communication impairments. Participants either responded to questions in semi-structured interviews that were audio-recorded or through online free response surveys. All transcripts and online free responses were analyzed using a consensus coding and modified grounded theory approach [2], supplemented by a directed content analysis [3]. Four themes emerged. (1) Disease progression may contribute to the trade-off between speed and accuracy with communication BCIs. (2) Individual experiences with technology use inform views about the speed-accuracy trade-off. (3) There is a range of views about how slow or inaccurate communication may impact relationships, the integrity of a message, and quality of life. (4) Design solutions are proposed by participants to address trade-offs in communication BCIs. Pertinent quotes will be shared.

Discussion: Engineers, developers and researchers often consider speed the gold standard for communication BCIs. Respondents told us that speed may not always be the most critical value in all situations. The context, partner, message and environment affect whether augmented and natural speakers prioritize speed or prioritize accuracy in any communication exchange. Developers and researchers need to measure more than information transfer rate or words per minute. Communication plays a critical role in many aspects of life that users value, their relationships, self-concept, and connections to the world. These values need to be integrated into the design and evaluation of communication BCIs.

Significance: This research emphasized the importance of exploring preferences and values for the speed-accuracy trade-off with individuals who experience the full range of communication impairment, those already using AAC and those who are anticipating future use of BCI technologies. Often, input for BCI design does not include individuals who experience disability [4]. The potential end-users in this research should shape the design, training and implementation of communication BCIs.

Acknowledgements: Grant funding was received from NIH/NIDCD R01DC009834

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Deep learning-based diagnosis of tinnitus using EEG signals

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Introduction: Tinnitus is a neuropathological phenomenon caused by the recognition of external sound that does not actually exist. Existing diagnostic methods for tinnitus are rather subjective and complicated medical examination procedures. The present study aimed to diagnose tinnitus using deep learning analysis of electroencephalographic (EEG) signals while patients performed auditory cognitive tasks.

Material, Methods, and Results: Patients with tinnitus (n=11) and age/sex-matched healthy volunteers (n=11) performed an active oddball task and a passive oddball task during EEG acquisition. During the active oddball task, patients with tinnitus could be identified with an area under the curve (AUC) of 0.886 through a deep learning model (EEGNet [1]) using EEG signals (Fig. 1A). Importantly, an analysis of the EEGNet convolutional kernel weights revealed interpretable tinnitus-related features in the alpha band, consistent with prior literature (Fig. 1B).

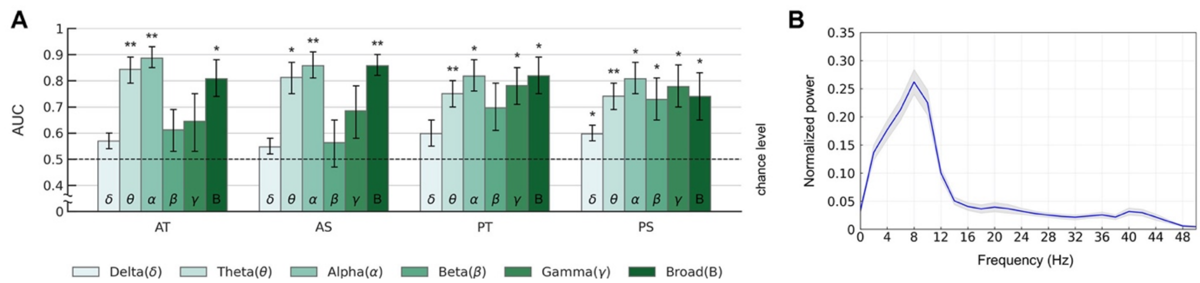

Figure 1. EEGNet model classification performance of tinnitus patients vs. healthy controls in the EEG oddball task. *A) AUC scores of the EEGNet model across different frequency bands and stimulus types. B) Normalized spectral power of the weights of the first EEGNet convolutional layer. Weights were projected on the frequency domain using Fast Fourier Transform. AT: active oddball task, target stimuli; AS: active oddball task, standard stimuli; PT: passive oddball task, target stimuli; PS: passive oddball task, standard stimuli. Error bars represent standard errors of the mean (*, $p < 0.05$; **, $p < 0.005$).*

Discussion: This study demonstrated that human EEG signals provide promising tinnitus identification features, particularly in EEG alpha band, that enable practical tinnitus-diagnostic applications.

Significance: Our findings suggest that task-relevant EEG features can be considered a neural signature of tinnitus symptoms and support the feasibility of EEG-based deep-learning approach for the diagnosis of tinnitus.

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Does Gender Matter in Motor Imagery BCIs?

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Introduction: A major issue in application of Motor Imagery Brain-computer interfaces (MI-BCI) is BCI inefficiency, which affects 15-30% of the population [1]. Several studies have tried to examine the effect of gender on MI-BCI performance [2,3], however the reports remain inconsistent due to small sample sizes and unequal gender distribution in past research. Hence, this study aimed to address this gap by collecting a large sample of female and male BCI users and investigating the role of gender in MI-BCIs in a reliable and generalizable manner.

Methods and Results: Using openly available datasets [1,2,4,5], we gathered a large EEG dataset including 248 subjects (123 females, 125 males, M_{age}= 23.86) who completed a similar two-class (left vs. right hand) MI protocol. Our analysis consisted of extracting Mu Suppression Index, which is indicative of mu-band (8-13 Hz) suppression in contralateral hemisphere compared to the ipsilateral one [1]. The Mu Suppression Index was calculated separately for each task (left and right-hand imagery) and then compared between gender groups. The results indicated no significant difference in the Mu Suppression Index of left ($t(246) = -1.69$, $p = .09$) and right MI ($t(246) = 1.26$, $p = .21$) between women and men.

Discussion: Contrary to the previous reports that suggest females can better modulate mu rhythm desynchronization during the MI task [1,6], our findings show no evidence for such superiority when the sample is sufficiently large and balanced to suppress the confounding effect of other variables such as an individual's personality and cognitive skills [2].

Significance: The findings shed light on the BCI inefficiency problem and guide development of future MI-BCI systems, e.g., by reconsidering gender-specific classification approaches [7].

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EEG Channel Selection Based on Feature Importance for Epileptic Seizure Classification

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Introduction: Classification of epileptic seizures based on electroencephalography (EEG) is a well-established research area. Most research uses a patient-dependent approach, i.e., training and test data come from the same patient. In order to use the results on other patients, a patient-independent model needs to be developed. The patient-independent model has to combine high accuracy, few features, and few channels in order to be fast and easy to use. This work presents both a patient-dependent and a patient-independent approach for epileptic seizure detection.

Material, Methods and Results: CHB-MIT and Siena Scalp EEG databases were used [1, 2]. Both use the 10-20 system for electrode placement. The EEG signals from the CHB-MIT database were first decomposed into four sub-bands using the Discrete Wavelet Transform (DWT), from the sub-bands sixteen features were extracted. To classify seizure and seizure-free periods, the features were used as input for Random forest (RF), Gradient Boosting (GB), and Support Vector Machine (SVM). The patient-dependent method was used as a starting point for the patient-independent method and to verify the high performance. Verification included balancing and unbalancing the dataset, changing the size of the training set, using different performance measures, and running the algorithm on the Siena Scalp EEG Database.

For the patient-independent method, the feature importance for each machine learning method was found using Mean Decrease in Accuracy (MDA), and the most important features were chosen. These features were used to find the channel importance using Mean Decrease in Impurity (MDI). Petrosian fractal dimension was found to be the most important for RG and GB over all channels, while standard deviation, root-mean-square, Katz fractal dimension were found to be the most important for SVM over all channels. The accuracy when using these features and the one most important channel are presented in Table 1. The average accuracy for the patient-dependent method is shown in the same table.

	RF	GB	SVM
Patient-dependent	**0.999**	0.996	0.992
Patient-independent	**0.976**	0.884	0.964
	FT9	F7	FT10

Table 1: Accuracy for epileptic seizure classification. The indicated channel is the one found to be most important. Standard deviation ±3%.

Discussion: RF is the method that gives the best results, although they all perform well even with only one feature and one channel. A clear conclusion on Which feature and channel give the best performance is not given due to variations in results for each run of the method. Results presented are from one run. The analysis of MDI and MDA for the selection of features and channels in different runs, in addition to why different runs yield different performance, is left for further work. Nevertheless, high-performance measures for the patient-dependent and patient-independent method were obtained.

Significance: Using only the most important electrodes, the vision is that patients can be notified on a portable device when a seizure occurs and, in the future, before it occurs.

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How do Ethical Concerns differ in Active and Passive Brain-Computer Interfaces?

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Introduction: Brain Computer Interfaces (BCIs) are intelligent systems that enable direct communication between the human brain and machines [1]. While BCI systems are promising for future medical and non-medical applications, studies concerning their ethical considerations are growing [2-6]. However, no previous study has examined how the public's ethical perception of the BCI technology is affected by the particular BCI type in question. This study thus considered whether the public experienced active and passive BCIs differently in the prominent ethical domains of personhood, responsibility and privacy.

Methods and Results: A within-subject survey consisting of pre-existing questionnaire items about the aforementioned ethical concerns was conducted amongst 34 students (17 males, between 19 and 36 years old, M_{age}=25.3, SD_{age}=3.9). Results suggest that active BCIs induce a higher ethical concern regarding personhood (Fig. 1), and that women experienced privacy to be more concerning in passive BCIs compared to active BCIs (p = .03).

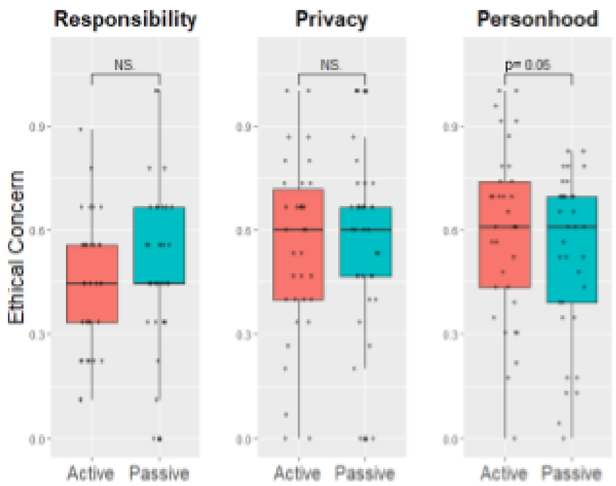

Figure 1. Boxplots of the normalized total score per ethical domain, for each BCI subtype. A significant difference between the two subtypes was found for personhood only.

Discussion: Our results show that particular concerns need to be addressed when developing future BCI systems. Privacy and personhood seem to raise more concern than responsibility, which echoes previous research indicating general worry about BCIs and personhood in particular [2-3,5].

Significance: This study suggests that the two types of BCIs might require different considerations for mainstream adoption by the public, and provides preliminary insights for the development of ethically informed BCI systems.

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Source Analysis of Directed Brain Connectivity During Opposite Neurofeedback Tasks

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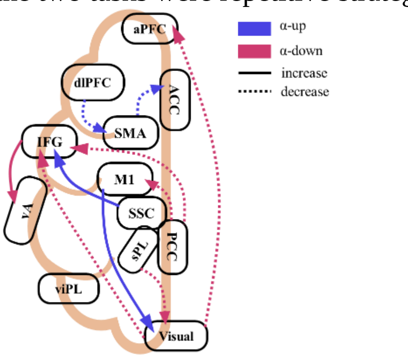
Introduction: Neurofeedback (NF) is a form of BCI based on operant conditioning. It can be used as a stand-alone intervention, to treat a variety of conditions or symptoms (e.g., anxiety, neuropathic pain), or training for assistive BCI devices [1]. One ubiquitous paradigm is alpha-power NF. To harness NF benefits, it is of utmost importance to deepen our understanding of externally (NF-) controlled brain dynamics. This study aims to compare directed connectivity changes and related mental strategies during NF for alpha upregulation (α-up) and downregulation (α-down).

Materials, Methods and Results:
22 able-bodied volunteers (age 27 ± 6, 7F) had three sessions of visual EEG-NF for alpha power modulation from electrode Cz, overlapping M1, the primary motor cortex (α-up n = 7; α-down n=15). The interface indicated power modulation as bars changing colour (green-red) and height. Participants revealed modulation strategies at the end of each session. Directed transfer function (DTF) was used to estimate frequency domain connectivity from sources reconstructed with sLORETA based on 64-channel EEG, between regions of interest selected a priori, spanning a NF network (NFN) [2], [3], the default mode (DMN) and frontoparietal networks (FPN), as indicated in Fig. 1.
Notable changes in alpha-band DTF (Fig. 1) include increased outflow from SSC to IFG and reduced connectivity between dlPFC-SMA-ACC in α-up, and decreased outflow from PCC and visual cortex during α-down. To achieve α-up, participants reported strategies based on mind clearing and breath focus, while for α-down, these were feedback- (“demand bar decreases”), planning- and emotion-related. Common to the two tasks were repetitive strategies (counting, mental arithmetic, focus on one word).



aPFC	- Anterior prefrontal cortex (DMN)
dlPFC	- Dorsolateral prefrontal cortex (DMN, FPN, NFN)
IFG	- Inferior frontal gyrus (FPN)
SMA	- Supplementary motor area (FPN, NFN)
ACC	- Anterior cingulate cortex (DMN, NFN)
M1	- Primary motor cortex
SSC	- Somatosensory cortex
vA	- Visual association area (NFN)
sPL	- Superior parietal lobule (FPN)
vIPL	- Ventral inferior parietal lobule (DMN)
PCC	- Posterior cingulate cortex (DMN)
Visual	- Visual cortex

Fig. 1 *- Directed connectivity in alpha band during NF compared to rest, blue- α-up, red- α-down tasks, and abbreviated regions of interest (assigned networks). Solid line = increase from rest, dotted line = decrease from rest, arrows point from source to sink.*

Discussion:
Relaxation strategies in α-up NF are reflected in reduced connectivity to IFG, the activity of which decreases with body relaxation, while increased outflow from SSC (adjacent to M1) points at attempted regulation of the target region. Decreased dlPFC to SMA connectivity might indicate efforts to relax and reduce mind-wandering. Reduction of PCC outflow (α-down) indicates undistracted concentration, and possibly more homogeneity of strategies in α-down NF compared to α-up. Information flow was reduced between FPN and both DMN and NFN in both tasks.

Significance:
Comparing connectivity in opposite NF tasks reveals brain network changes associated with NF processes in general, and those that are task specific. The changes reflect participants’ mental strategies.

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Virtual Physical Model-based Brain Switch via Periodic SSVEP Modulation for Asynchronous Brain-Computer Interfacing

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Introduction: Brain switches provide a tangible solution to asynchronized brain-computer interface (aBCI), which decodes user intention without relying on a pre-programmed structure. However, most brain switches based on electroencephalography (EEG) signals have high false positive rates (FPRs) [1], resulting in high frustration and less practicality [2]. Here, we propose a novel virtual physical model-based brain switch that leverages periodic SSVEP modulation to achieve low FPR and robust triggering time.

Material, Methods and Results: EEG data were recorded for eight subjects by a 64 channel Biosemi ActiveTwo system, among which EEG channels over occipital cortex are utilized to be the online control signals. Each subject performed 21 brain-switch triggers to evaluate the triggering time performance. Then, each subject started a one-hour-video-playing task to evaluate the FPR during non-triggering resting state (**Fig. 1a**). The Institutional Review Board of Shanghai Jiao Tong University approved the study protocol. EEG signals from the selected channels were preprocessed and EEG features were extracted via canonical correlation analysis (CCA). The correlation coefficient features (to 15Hz and 20Hz reference signal) are mapped to a virtual force. Then the virtual force (modulated by gazing at different SSVEP stimuli) could periodically drive the virtual physical system to accumulate it's swing amplitude until the switch was triggered (**Fig. 1a**).

(a) (b) (c)

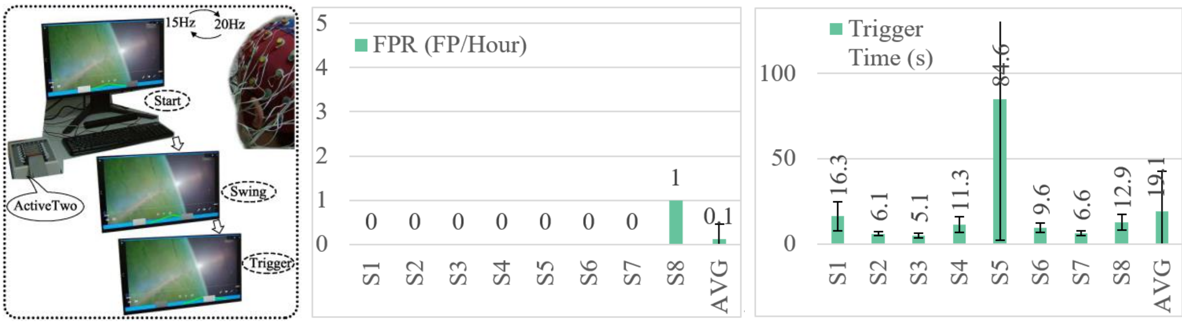

Figure 1. *(a) Experimental paradigm for brain switch evaluation. (b)FPR of each subject during the one-hour-video-playing task . (c) Trigger time of each subject during the active triggering task.*

Figure 1b showed the FPR of each subject during the one-hour-video-playing task. During the one-hour-video-playing, only subject S9 had one false alarm triggering. The average FPR was 0.13±0.33FP/hour during the video-playing. The brain switch's triggering time is given in **Fig. 1c**, demonstrating that most subjects could trigger the brain switch within 16.3s. The best performance was gained by the subject S3, whose triggering time was 5.1s on average, and half of the subjects could trigger the brain switch within 10.5s (the median). The average active-triggering-time (19.1s) was less than one thousandth of the time for a false alarm triggering happened (8h).

Discussion: With the interactive operation mode during the brain switch triggering process, the subjects could modulate the SSVEP feature and drive the virtual physical system to trigger a brain switch when they want. The virtual physical system built up a coding and decoding strategy based on its resonance phenomena, which could be easily understood and accepted by the users. The coherent periodic active modulation would utilize the resonant frequency to trigger the brain switch, while incoherent noise only causes limited swing amplitude.

Significance: This work first time showed that the SSVEP-based BCI was capable to provide high reliability and efficiency for brain switch control. The FPR was as low as 0.13FP/hour while the median triggering time was 10.5s in our pilot evaluation. This is promising for the future development of BCI applications.

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Evaluating implant locations for a minimally invasive speech BCI

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Introduction: Expressing thoughts through vocalizations is a natural form of communication that can deteriorate in individuals suffering from a stroke or a neuromuscular/neurodegenerative disease. Speech brain-computer interfaces (BCIs) have the potential to restore this communication channel by reconstructing speech directly from recorded neural signals. Many of the current feasible technologies require a relatively large craniotomy to implant the BCI device. Stereo-electroencephalography (sEEG), on the other hand, only requires small burr holes for implantation, thus reducing the risks associated with the surgical procedure. The sEEG electrodes have a viable potential for long-term BCI use, as the leads are similar to those used for chronic deep brain stimulation. They are routinely implanted in epilepsy patients to detect the epileptogenic zone, usually with a distributed coverage across multiple cortical and subcortical regions. Our large number of recordings with these patients allows us to investigate which electrode shaft location has the best potential for a speech BCI.

Methods: We collected overt speech production data in over 30 participants implanted with multiple sEEG electrode shafts (Fig. 1). Acoustic and sEEG signals were recorded simultaneously and were time-aligned. The sEEG signal was re-referenced to the average signal within each shaft. The neural signal was further divided using 50ms overlapping windows. We considered neural features up to 200ms prior to and including the frame aligned with the audio for reconstruction. We used a unit-selection approach in a 10-fold cross-validation for each individual shaft and each participant separately.

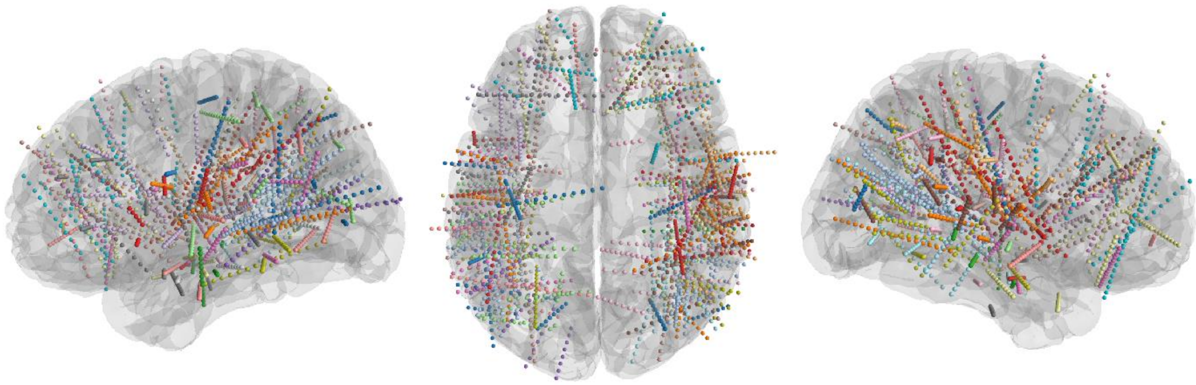

Figure 1. *Electrode shaft locations from included participants on an average brain. Each color represents one participant and each sphere represents one electrode channel.*

Results and Discussion: We evaluate the feasibility of reconstructing speech using a single sEEG electrode shaft by correlating the spectrogram of the original speech waveform to that of the reconstructed waveform. Electrode shafts covered nearly all regions of the brain (Fig. 1), although the occipital and frontal lobes were less densely covered than the temporal and parietal lobes. Electrodes were equally distributed between the two hemispheres. We investigate, across all participants and shafts, which location results in the strongest correlation. We focus on a comparison between hemispheres, lobes, depth and size of the electrode.

Significance: This work contributes to making an informed decision for the electrode placement of a (minimally invasive) speech BCI. Decreasing the necessary size of the craniotomy and the amount of implanted electrodes could reduce the burden on the patient.

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Subdural ECoG Recordings of High-frequency Activity from a Wireless Implantable BMI Device

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Introduction: Brain machine interfaces (BMIs) are a promising tool to assist communicating and motor functions for individuals with severe motor disability[1]. Prior to clinical application, recording performance must be sufficiently confirmed by animal experiments. In this study, we aimed to evaluate the performance of a customized BMI wireless device for recording ECoG signals in two nonhuman primates.

Material, Methods and Results: We customized a wireless device for implantable BMIs for clinical application[2]. We implanted thirty-two electrodes subdurally over the left temporoparietal cortex on two monkeys. We evaluated the recording performance of the wireless device by ketamine-induced responses. Result: The devices successfully recorded and transmitted broadband frequency activities. Spectral analysis of raw signals demonstrated that the devices detected characteristic results of high-frequency band activity induced by ketamine injection (Figure1).

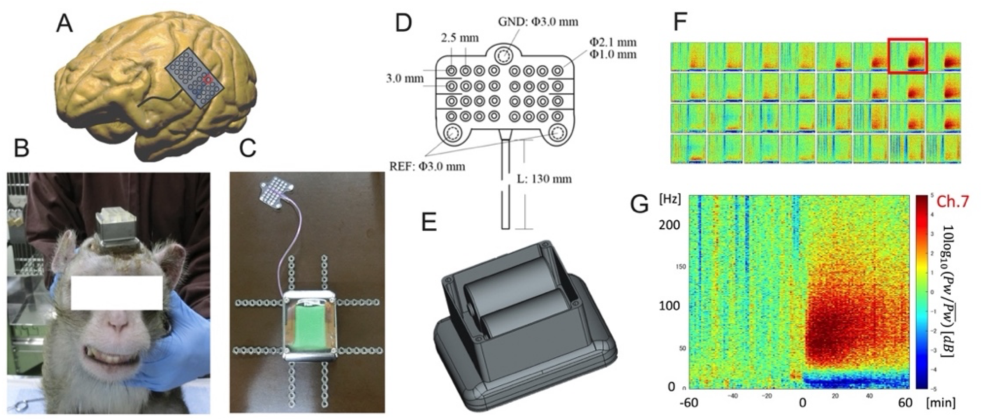

Figure: (A) The location of the 32 implanted electrodes. (B)The monkey with implanted device. (C) A photograph of the device ready for implantation. (D) The 32-electrode silicone-based array. (E) Computer-aided design model showing the assembly of the device. (F) Spectrograms results of all 32 electrodes showing the power changes after ketamine. Each subgraph represents the one electrode in (D). (G) Representative spectrograms of channel 7 (surrounded by a red outline in F). The time course included a 60-min baseline and 60-min recording after ketamine.

Discussion: We confirmed the functionality of the wireless device in recording and transmitting electrocorticography (ECoG) signals with required bandwidth and recording stability.

Significance: These results provide confidence that this wireless device can be a translational tool for other fundamental neuroscientific studies in free-moving models.

Acknowledgements: We sincerely thank all the staff of Candidate Discovery Science Labs., Astellas Pharma Inc., who handled and fed the monkeys used in this study and supported all experiments in this study.

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The theta-to-alpha ratio represents a convenient task independent measure of brain workload

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Introduction: Human error is often a result of sustained cognitive stress and/or vigilance. In a working environment this can have dramatic consequences, whereas in video-game settings it can lead to a loss of motivation. In both fields, an objective and task independent way of measuring brain workload would help in creating adaptative systems to avoid these effects. The theta/alpha ratio (TAR) was proposed as an index of workload that increases with the number of simultaneous tasks [1, 2]. We wondered if this index could be used as well to measure varying difficulties within a set of different tasks.

Material and methods: We measured 30-channel EEG in 9 healthy subjects while they were performing several tasks at two different levels of difficulty, followed by subjective workload report with NASATLX. The tasks consisted of two working memory tasks, Nback and Sternberg and two video game like tasks controlled by movement of the wrist, the flying car [3], (see Figure 1 left) and a gameplay copy of it without the engaging 3D environment. Frequency bands power and TAR were extracted, and their values compared in between levels.

Results: NASATLX rating and TAR were significantly higher in the difficult level compared to the easy one in every task except for Sternberg (Figure 1 right, $p < 0.05$ for level effect), where only the TLX rating was different.

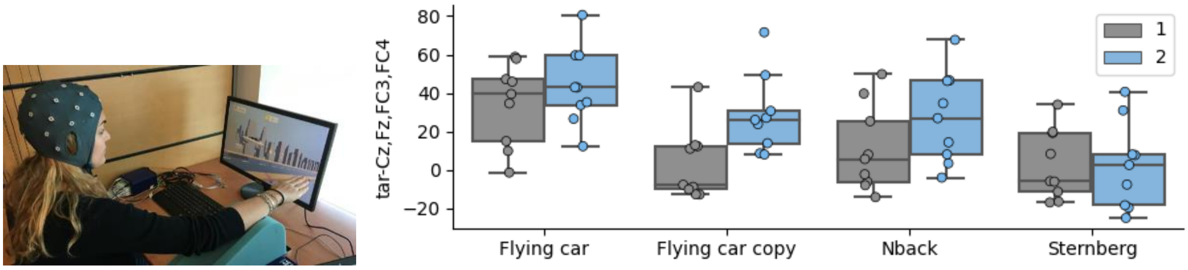

***Figure 1.** (Left) Experimental setup. (Right) Frontal TAR is higher at level two for all tasks except Sternberg. TAR is normalized on a resting period before the tasks and grouped by task and level 1 or 2. Repeated measure ANOVA: task $F_{(3,24)} = 9.69$, $p = 0.001$; level $F_{(1, 8)} = 27.94$ $p = 0.0007$; interaction $F_{(3, 24)} = 3$, $p = 0.05$.*

Discussion: This result confirms that the TAR index is a highly promising measure of brain workload, and that it seems to be mostly independent of the type of task, requiring either more cognitive resources or more vigilance.

Significance: We hope to provide complementary insights on the TAR and contribute to revealing its usefulness as a marker of generic brain workload. Thanks to the possibility of measuring it using only one or two electrodes, and its ease of calculation, it represents a promising target to be implemented in a multi applications commercial EEG device.

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EEG-based Automatic Emotion Recognition Using Machine Learning

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Introduction: The field of EEG-based emotion recognition has been widely explored in the last decade. Methods proposed by recent literature mostly use complex deep learning methods to achieve good predictions. To obtain comparable results using simpler machine learning techniques would be preferable as these models are much more intuitive to implement and understand. This work explores support vector machine (SVM) classifier on two datasets (DEAP and SEED) and compares the performance with more complex models.

Material, Methods and Results: This work uses the publicly available datasets, DEAP [1] and SEED [2], to evaluate SVM. The preprocessed EEG data from DEAP is segmented into one-second epochs without overlapping, resulting in total 2400 epochs. Further, it is filtered into four frequency sub-bands using the Butterworth bandpass filter. The data from SEED is also segmented into epochs of one second without overlapping, resulting in a total of 3394 epochs. Several features and their different combinations are extracted from each epoch of the EEG signal. For DEAP, the same features are derived for each one-second epoch in a three-second baseline recording. The computed features for each trial are corrected by subtracting the average value of the baseline features. To decipher the emotions, the extracted features are used as an input to SVM with RBF kernel and K-nearest neighbor (KNN) classifiers. The performance of SVM is found to be superior as compared to KNN. The best average accuracies achieved for each dataset are presented in Table 1. For DEAP, the most suitable feature set is the combination of Hjorth mobility (HM), Hjorth complexity (HC), differential entropy (DE), frequency bands energy (FBE), and Hjorth mobility spectrum (HMS). For SEED, the feature HM is found to be more useful than the combination of several features in detecting human emotion. The performance of the SVM on both datasets is verified using a 5-fold cross-validation approach.

Dataset	Feature	Accuracy
DEAP arousal	HC, HM, DE, FBE, HMS	96.71 %
DEAP valence	HC, HM, DE, FBE, HMS	96.50 %
SEED	HM	83.87 %
SEED	HC, HM, DE, FBE, HMS	63.76 %

Table 1: *Mean accuracies*

Discussion: It can be observed from the obtained results that the simple machine-learning techniques can produce satisfactory predictions for EEG-based emotion recognition. The obtained results for the model proposed for DEAP are comparable to the ones obtained with deep learning [3]. For SEED, deep learning methods outperform the best-performing proposed model by almost 11 percentage points [4]. Nevertheless, both the proposed models show promise for utilizing simpler models in EEG-based emotion recognition. In future work, a new dataset will be developed to test the generalization of the proposed machine-learning method. And, a channel selection approach will be adopted for complexity reduction of the models. Related studies [2,5] have shown that the number of electrodes can be reduced significantly without decreasing the prediction accuracy of the model.

Significance: The potential for emotion recognition devices will be huge both medically and commercially given that only a few electrodes in combination with simple and fast models perform well.

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Using Autoencoders to Denoise Cross-Session Non-Stationarity in EEG-Based Motor-Imagery Brain-Computer Interfaces

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Introduction:
A major problem in motor-imagery (MI) brain-computer interfaces (BCIs) relates to the non-stationarity of brain signals. Consequently, the performance of a classifier trained for an individual subject on a certain day deteriorates during the following days. The traditional approach is to recalibrate the algorithm every session, limiting the wide use of BCIs.

Materials, Methods, and Results:
Here, we use an autoencoder (AE) convolutional neural network to identify a low dimensional representation of the EEG signals from the first day (or days) and show that this allows for stable decoding performance on the following days without resorting to recalibration. Furthermore, we demonstrate that the residual signals, namely the difference between the original and reconstructed EEG, can be used to accurately discriminate among different recording sessions. In line with that, the reconstructed EEG cannot be used to discriminate among recorded sessions. This implies that the reconstructed EEG reflects an invariant representation of the subject's intent, whereas the residual signals reflect a non-stationary component, which differs from one session to another. Results from an application to MI data from a stroke patient are depicted in Figure 1. As can be seen, the performance of our algorithm with no recalibration (green) is equivalent to that of a benchmark classifier which is recalibrated (blue). In contrast, training a Naïve classifier with no recalibration (red) achieves poorer performance.

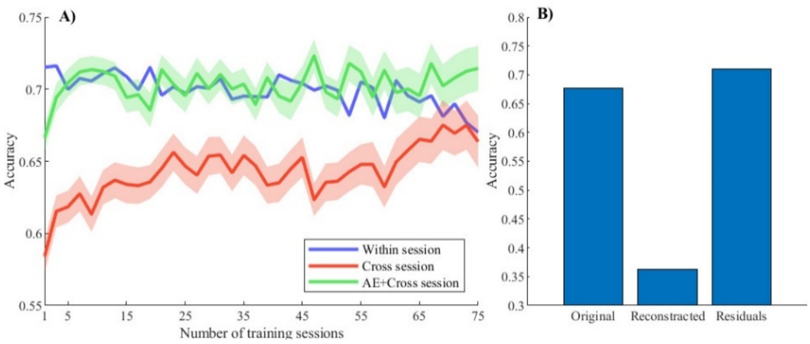

Figure 1: Analysis of longitudinal data (134 daily sessions) from a stroke patient. **A)** Mean accuracy of different models. The cross-session (red) and AE + cross-sessions (green) models were trained on an increasing size of the training set and were tested on the remaining sessions. The within-session benchmark (blue) is the score of the cross validation on the test set (no inference on new sessions). The shaded area represents the standard error of the accuracy across sessions. **B)** Mean accuracy of origin session classification using the original signals, reconstructed de-noised, and residuals signals.

Discussion:
Autoencoders can be used to identify a low-dimensional invariant representation of subject intent, which can minimize or eliminate recalibration. Analyzing the residual signals can provide further insights into the sources of signal non-stationarity. The approach can be generalized to incorporate weakly-supervised methods.

Significance:
The approach relies on an unsupervised learning framework which can be easily incorporated (without additional data collection) to increase the stability of BCIs and bring them closer to wide adoption.

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Investigating the proper time to perform the motor imagery task in a multimodal BCI

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Introduction - In the paradigm of EEG motor imagery BCI, one of the challenges is to elicit brain patterns that are differentiable to ensure a good discrimination for machine learning algorithm[1]. Using a robotic arm is a way to trigger the brain into doing the motor imagery task. The degrees of freedom cannot be dealt solely by a MI BCI most of the time limited to four classes in complex and demanding for the subjects scenarios. In that context, a solution is to couple the BCI with another technology such as eyetracking [2]. This coupling allows to control the position reached by the robot's gripper via gaze and the closing of the hand via the MI task in an intuitive way closer to real directed grasping movements. In this framework; we decide to interrogate the appropriate moment to perform the MI task during a shared control between gaze and BCI.

Material, Methods and Results - We propose 3 configurations to answer the problematic: one where the task of MI/rest is performed prior to the robot's movement (Strategy 1), one after the movement (Strategy 2) and one while the robot is moving (Strategy 3). We investigate differences of performances and difference of power spectrum in the α and β bands in the sensorimotor cortex between strategies. Each strategy consists of 3 phases, one phase of calibration where subjects receive only positive feedback, the robotic arm closes its gripper at each MI task. And two phases of driving (Drive 1 & 2) where subjects receive feedback based on their neural activity (the robotic arm closes its gripper if the machine learning algorithm classifies accurately the MI task). Between phases, a LDA is trained on the feature of interest (electrodes in the sensorimotor cortex at a chosen frequency) based on the R^2 map of electrodes and frequency bands shown during the previous phase. 10 subjects(4 Males aged 25,3 ± 2,4) performed over 3 weeks the different strategies in a randomised way. Figure 1 presents the main results in terms of power spectrum contrast maps and the protocol setup. During Drive 1, we obtain in average in accuracy 63%,65% and 65% (Strat 1,2,3 respectively) and 79%,91% and 86% in sensitivity. During Drive 2, we obtain in average in accuracy 72%,75% and 75% (Strat 1,2,3 respectively) and 81%,78% and 81% in sensitivity.

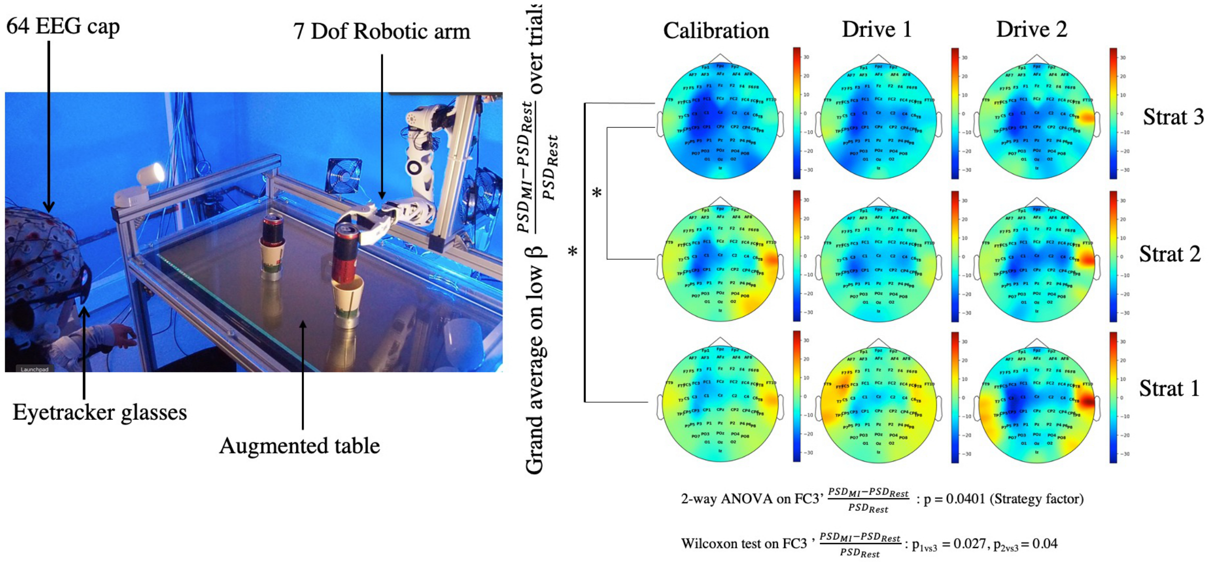

Figure 1: Left : Setup composed of the eyetracker, the robotic arm, the EEG cap and the augmented table(a red dot appears under the can for MI task and a blue dot for resting state), Right : grand average analysis of the subjects ERD on low β band (13-25 Hz)), Wilcoxon test performed on the ERD between strategies on relevant of the sensori motor cortex based on 2-way ANOVA test $p < 0.05$ between strategies.

Discussion and Significance - First, from the ERD perspective, we observe that the strategy 3 induces an activity significantly different from strategies 1 and 2. Moreover strategy three seems to activate more networked areas than the other two, meaning that having the robot moving during the MI task could induce extra cognitive process.

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What is the exact relationship between beta band activity and hand motor imagery?

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Introduction: The characterization of the event-related desynchronization (ERD) and synchronization (ERS) phenomena in the mu and beta frequency bands [1] almost three decades ago marked the discovery of the first reliable non-invasive markers of brain activity during motor-related tasks. Since then, the Brain-Computer Interface (BCI) community has heavily relied on band-limited power changes as the classification feature of interest, developing algorithms that best capture relative differences across experimental conditions. However, recent findings in neuroscience have challenged the idea that signal power best describes the movement-related modulation of brain activity, especially in the beta frequency band. Beta band activity has been shown to occur in short, transient events rather than sustained oscillations on a single-trial level [2]. This finding implies that the ERD/S patterns only emerge as trial-averaged activity markers and that signal power may, thus, not be able to capture all relevant brain activity modulations during motor-related tasks. The analysis of beta band burst activity has the potential to provide access to activity markers that are at least as sensitive as beta power in terms of classification, and that could describe more subtle changes of condition-specific activity.

Material, Methods, Results: Pursuing this hypothesis, we analyzed the activity of channels C3 and C4 during “left” and “right” hand motor imagery from an open EEG dataset [3]. Using a new burst detection and waveform analysis algorithm [4], we show that classification features that describe the modulation of burst rate for bursts with distinct waveforms can be more informative than beta band power and are more reliable than conventional burst activity representations such as the overall burst rate, burst peak amplitude, and the temporal and frequency spans of bursts (see Fig. 1).

Discussion: These results shed light on the non-linear relationship between beta burst activity and band power, emphasizing that the field of BCI can benefit from incorporating recent neurophysiological findings.

Significance: This work serves as a proof-of-concept for constructing a suitable-for-classification representation of beta burst activity in the context of motor-related BCI paradigms.

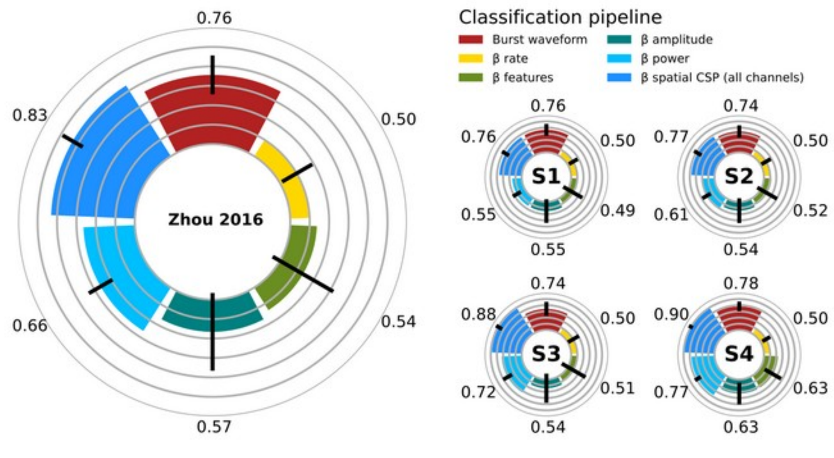

Figure 1. Average and subject-specific classification scores based on different feature extraction algorithms for the Zhou 2016 open motor imagery dataset in “left vs right hand” task.

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Longitudinal Intervention of VR-based BCI Training: A Case Study of Chronic Stroke Patients

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Introduction: There is increasing evidence of the impact of Motor-imagery (MI) Brain-Computer Interfaces (BCI's) in stroke rehabilitation [1][2]. MI practice can be augmented through embodied feedback delivered by virtual reality (VR). Nonetheless, detailed information concerning the impact of VR-BCI training in clinical outcome is still largely missing. This abstract illustrates the long-term effect of VR-BCI training in sensorimotor patterns and clinical scales of stroke patients.

Material, Methods and Results: Seven chronic stroke patients underwent a 3-week VR-BCI intervention. Fugl-Meyer Assessment (FMA) was conducted pre-, post- intervention, and a follow-up, one-month later. The VR-BCI training consisted of a bimanual rowing task (NeuRow) involving MI and motor observation [3]. From the EEG, the Event-related Desynchronization (ERD) was extracted from the Mu band (8-12 Hz). All patients showed significantly increased Mu ERD compared to baseline, however, the affected side showed reduced ERD during the contralateral MI. Significant ERD differences originating from both the lesioned and the healthy hemisphere were found when comparing post- with pre- intervention in all patients, and decreasing ERD was found for patients with no clinical improvement. Patients with decreased lateralization of ERD had no improvement of the FMA score (fig.1).

Conclusion: Stroke patients in the chronic phase can modulate their brain activity patterns using MI in a VR-BCI task, with observable patient-specific differences between brain activity and clinical outcome. Nonetheless, only patients with increased ERD lateralization showed clinical improvement.

Significance: These results add further evidence concerning the relationship of ERD features with clinical outcome in terms of FMA in an VR-BCI training paradigm in chronic stroke patients.

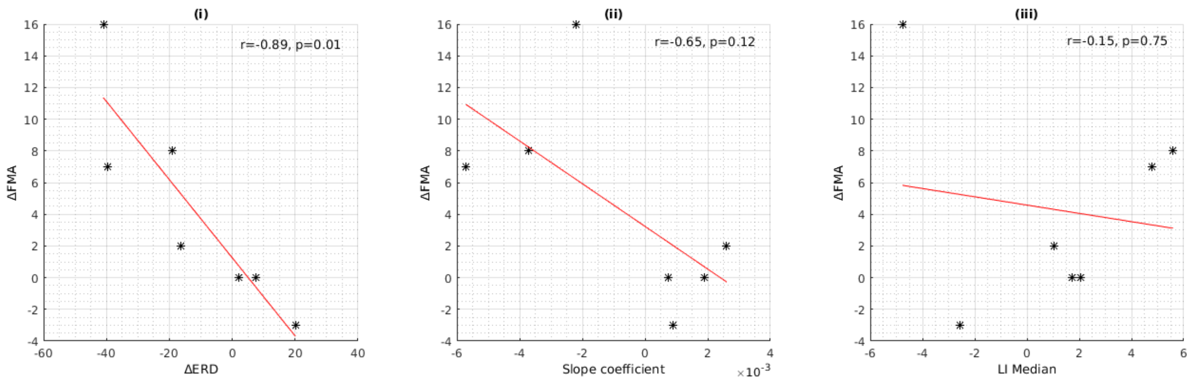

Figure 1. *Relationship of ΔFMA score between (i) pre-post- ΔERD; (ii) ERD steepness of the paretic side, (iii) LI of ERD.*

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Brain-computer interface for treatment of focal dystonia

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Introduction: Dystonia is a neurological disorder that causes involuntary muscle contractions leading to uncontrollable movements and abnormal postures. Current treatment options are limited to temporary symptom management [1]. Recent characterization of dystonia as a neural network disorder [2, 3] opened opportunities for the development of novel treatments for targeting disorder pathophysiology.

Methods: We developed a closed-loop neurofeedback-based BCI and tested it in 10 patients with laryngeal dystonia (LD; 5 M/5 F, age 57.1±12.3 years). The BCI included a high-density EEG system and a machine-learning platform (regularized LDA) to provide near real-time visual feedback of ongoing EEG activity, which was based on differences between symptomatic speaking and asymptomatic whisper, in a virtual reality (VR) environment (Fig 1A). Using individual feedback, each patient was trained to actively modulate and match their neural activity during symptomatic speaking to that of asymptomatic whisper. Each patient participated in 2 training sessions for 5 consecutive days. BCI-induced changes in neural activity were assessed by contrasting source power activations in the beginning vs. end of daily BCI intervention and using discriminative power (*R^2*) between speech and whisper spectral power across the entire length of intervention.

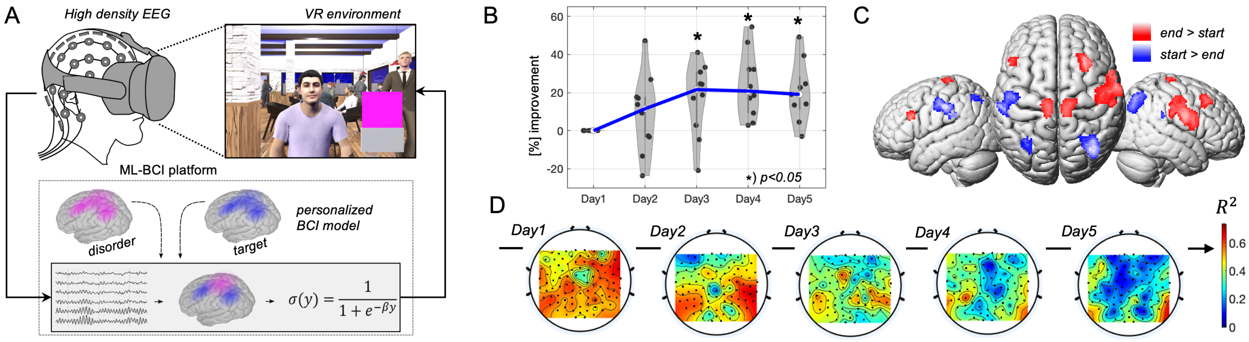

Figure 1. (A) BCI intervention paradigm in LD patients. (B) Controllability of feedback over the course of 5-day intervention. (C) Group BCI-induced gamma-power modulation; (D) Daily changes in gamma-power during symptomatic speaking compared to asymptomatic whisper.

Results: Patients demonstrated the significant ability to gain and maintain the control of their neural activity during BCI training using the near real-time visual feedback (Fig 1B). Most prominent BCI-induced neuromodulation was found in the gamma frequency band (30-50 Hz) and included a reduction of abnormal activity in the left primary sensorimotor and bilateral parietal cortex and an increase of activity in the right primary sensorimotor and bilateral premotor cortex (Fig 1C). Gamma-power differences between speech and whisper were gradually reduced from Day 1 to Day 5 (Fig 1D). In a 7-day follow-up after BCI intervention, 7 out of 10 patients reported improved voice quality and ease of speaking.

Discussion: The BCI intervention directly modulated brain regions associated with LD pathophysiology, which was associated with symptom reduction throughout the training and at a follow-up.

Significance: Closed-loop BCI interventions targeting disorder pathophysiology may be a novel treatment option for patients with laryngeal dystonia.

Acknowledgements: We thank NIH/NIDCD for study funding (R01DC019353 to KS).

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High-gamma band event detection improves stability of finger trajectories decoded from ECoG-LMP activity

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Introduction: It has been repeatedly shown that finger movement trajectories can be decoded from electrocorticography (ECoG) grids placed on the hand motor cortex [1]. However, even state-of-the-art methods exhibit instabilities between finger movement events (see Fig. 1). We propose a novel methodology that improves stability by modulating trajectories predicted from Low Motor Potentials (LMPs) by movement-related events predicted from gamma band activity.

Methods: Two Block-Term Tensor Regression [2] models are trained, one on LMP (< 3.5 Hz) ECoGs with data glove trajectories, and another on high gamma band (> 60 Hz) ECoGs with binarized trajectories, yielding, respectively, single finger trajectory estimates $x_{lmp}(t)$ and $x_{\gamma}(t)$. Equation (1) summarizes how the trajectory of a given finger is corrected into $y(t)$ using thresholded $x_{\gamma}(t)$ estimates:

$$y(t) = f\left(x_{lmp}(t), x_{\gamma}(t)\right) = \begin{cases} C, & x_{\gamma}(t) \leq \text{threshold} \\ x_{lmp}(t) \times x_{\gamma}(t), & x_{\gamma}(t) > \text{threshold} \end{cases} \qquad (1)$$

with C and the threshold subject- and finger-dependent parameters estimated through cross-validation thereby optimizing the cross-correlation between predicted and expected trajectories.

Results: The proposed method, when applied to Dataset 4 of BCI competition IV [3] with ECoG recordings of rapid single finger repetitions, yielded an average correlation coefficient of 0.56, in line with the state-of-the-art relying on multiband ECoG activity [2] or, in addition, on Riemannian-space features [4]. However, the stability during rest is quite different (Fig. 1). For example, for subject 1, the proposed method returns an average variance of 0.011, which is much lower than the 0.03 variance of decoder [2].

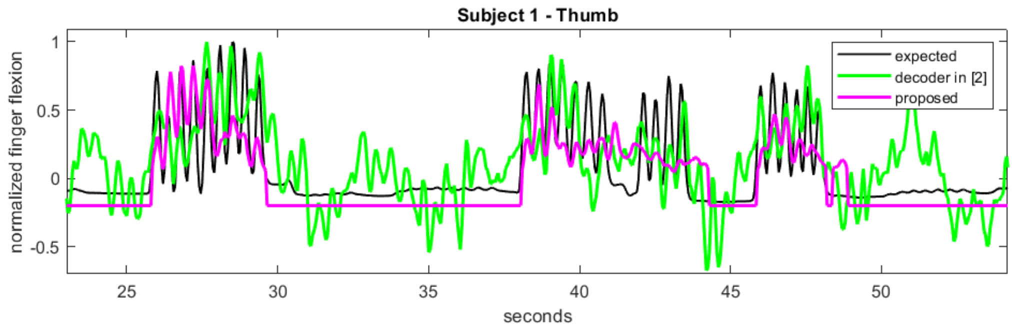

***Figure 1:** Expected thumb trajectory (black) and trajectories decoded using the proposed (pink) and the state-of-the-art method [2].*

Discussion: The improvements in stability obtained by the proposed method suggest that high gamma band activity distinguishes rapid finger movements from rest whereas LMPs codes for finger trajectories.

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Empirical evaluation on multiple BCI datasets of the functional connectivity ensemble (FUCONE) method

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Introduction - Mastering Brain-Computer Interface (BCI) control via a voluntary modulation of the cerebral activity remains a learned skill that around 30 % of BCI users cannot develop control after completing a training program. Among the approaches adopted to circumvent this limitation is the design of more sophisticated classification algorithms to better discriminate the subjects' mental state [1]. Riemannian geometry-based methods are now the gold standard by notably improving the robustness of the performance [2]. One could consider the subjects' specificity by using alternative features that reflect the interconnected nature of brain activity. Functional Connectivity (FC), estimating the interaction between different brain areas, is a promising tool for BCI [3] relevant to discriminate subjects' mental states [4] and to study brain network reorganization underlying MI-based BCI training [5].

Material, Methods and Results - In this study, we propose a new framework that consists in combining functional connectivity estimators (namely Instantaneous and Imaginary coherences), Riemannian geometry, and ensemble learning. We compared our approach to the state-of-the-art methods (namely two pipelines relying on the use of the common spatial patterns [6], [7]; and a third one based on a purely riemannian method [8]). To assess the robustness and the replicability of our approach, we tested it through a large number of subjects, datasets, and motor imagery tasks. For a complete description of the pipeline[1] and the datasets used in the replicability study one can refer to [6].

Results - FUCONE performed significantly better than all state-of-the-art methods in a meta-analysis that aggregated results across datasets. In the case of the classification of 2 classes (right hand vs feet), for four over five datasets, FUCONE showed the bests results in terms of average accuracy from 0.82 to 0.91, and variability from +/-0.08 to +/-0.14 (see Figure 1). The performance gain is mostly imputable to the increased robustness of the ensemble classifier with respect to the inter- and intrasubject variability.

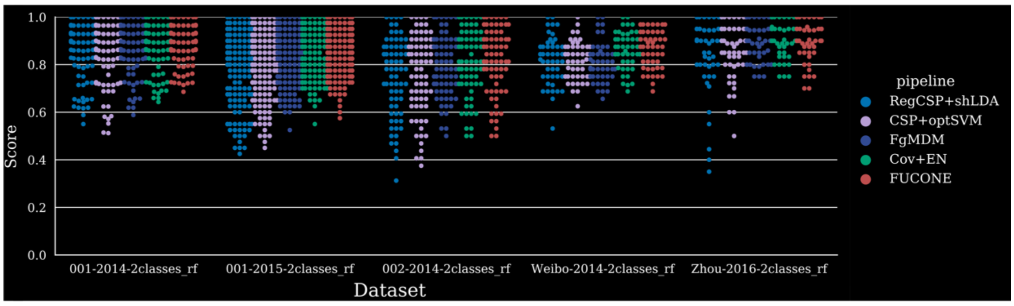

Figure 1 Replicability assessments and comparison with state-of-the-art pipelines. Analysis performed with 3-class (left hand vs right hand) datasets.

Discussion - Even though our approach enabled a reliable improvement of the BCI accuracy, we still observed an important inter-subject variability. Several elements can explain it: the strong diversity in terms of MI tasks and of the number of channels considered without preprocessing, and the variety in the possible ways to detect neurophysiological properties underlying the MI performance. Preliminary results in the source space, relevant to provide a description of the mechanisms underlying the control of a BCI, tend to demonstrate an improvement of the performance and a reduction of the inter-subject variability of our approach with respect to the state-of-the-art methods.

Significance: Our results offer new insights into the need to consider the interconnected nature of brain functioning to improve the BCI performance.

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[1] The code used to perform the analysis are publicly available in this Github repository: https://github.com/mccorsi/FUCONE.git

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Towards user-centric BCI design: Markov chain-based user assessment for mental imagery EEG-BCIs

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Introduction: Widespread use of brain-computer interfaces (BCI) is limited by "BCI Inefficiency," a phenomenon where users struggle to produce brain signals that are machine discernible [1, 2]. One avenue to reducing BCI inefficiency to improve user training procedures to enhance user performance. However, current classification algorithm-based methods for user assessment during training yield limited descriptive information about user performance and are prone to misrepresenting user performance progression, thereby hindering training [3, 4, 5]. Here, we propose Markov chain-based methods for user assessment that identify and describe a user's neural modulation abilities.

Material, Methods and Results: First, we used unsupervised clustering methods to segment the electroencephalography (EEG) signal space into regions representing EEG patterns that users had demonstrated the ability to produce. In contrast to supervised classifier-based methods, this approach does not rely upon identifying EEG patterns within trials of a particular task label and, consequently, the user-specific number of pattern states can be independent of the number of mental imagery tasks employed. Second, we modeled users as Markov processes moving through these pattern states (Fig. 1). Using the entropy rate and steady-state distributions of Markov chains, two metrics were developed to assess user ability to (i) maintain consistent patterns during task performance and (ii) produce distinct patterns while performing different tasks. Analysis of motor imagery datasets revealed significant correlations between these metrics and classification accuracy, demonstrating their ability to broadly reflect user skill.

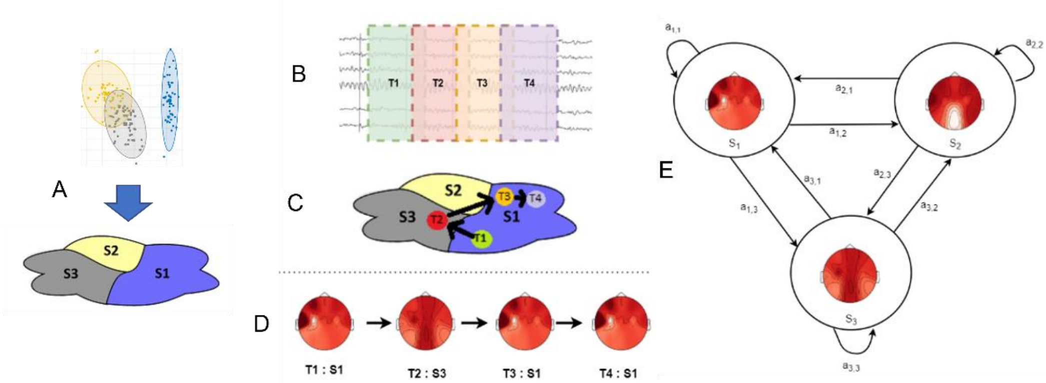

Figure 1. Outline of proposed method. (A) Apply clustering methods to define state space of distinct patterns users can produce, independent of task labels. (B) Segment trials into shorter temporal windows. (C) Observe the pattern state for each temporal window. (D) Represent trials as a stochastic sequence of pattern states. (E) Model transitions between pattern states as a Markov chain.

Discussion: The results indicate that BCI users' mental imagery skills can be estimated using a Markov state space without states or patterns explicitly defined as being associated with a particular task label.

Significance: The proposed metrics provide new avenues to develop (i) improved training schemes that target user weaknesses and enable more exploratory learning and (ii) BCI-design tools that enable the technology to be customized and optimized to leverage the strengths of each individual user.

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Identification of Tic Onset Biomarker from Chronic Recordings in Centromedian Thalamus and Globus Pallidus Interna for Closed Loop Deep Brain Stimulation in Tourette Syndrome

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Introduction: Tourette Syndrome (TS) is a neuropsychiatric disorder characterized by repetitive and involuntary motor and phonic tics. Most cases present symptoms that start and stop during childhood, but for up to 23% of cases, symptoms remain and can get progressively worse during adulthood [1], [2]. Multicenter retrospective studies have reported a 45.1-52.7% average decrease in tic severity [2] in patients with Deep Brain Stimulation (DBS), indicating it could offer an alternative therapy when symptoms become refractory. The most common nuclei targeted for conventional DBS are the Centromedian (CM) Nucleus of the Thalamus and the anterior Globus Pallidus Interna (aGPi) [3]. However, the paroxysmal nature of this disorder leads us to believe patients would benefit from closed-loop DBS therapy.

Materials, Methods, and Results: To test this, we implanted four patients (3 males, and 1 female) with bilateral macro electrodes targeting the CM, both connected to a rechargeable investigational neurostimulator from Medtronic (Summit RC+S, Medtronic PLC). This device, apart from delivering electricity to the region of interest, is also capable of streaming Local Field Potentials (LFP) and performing a linear discriminant analysis. After implantation, patients visit the center periodically for up to 24 months. During each visit we collect video, LFPs, electromyographic, and acceleration data while the patients are at rest (or holding the urge to tic as much as possible), voluntarily moving their hands when shown a cue, or freely ticking. Later, we align and mark down the data to separate each condition. After averaging across the runs where we stream data from sense-friendly configurations for the CM, we have identified a low-frequency (3-10 Hz) power increase occurring after tic onset. Using only this biomarker, we were also able to start closed-loop DBS in one subject thus far, reporting similar benefits to continuous stimulation with potentially fewer side effects and longer battery life.

Discussion: There are still many challenges left to find the optimal settings for each patient, due to the variable presentation of the tics and the psychiatric components of TS. These can make programming sessions time-consuming and tedious for the patient. Shortly, image and electrophysiological-informed decisions along with the adaptive capabilities embedded in new neurostimulators could make this process faster. To evaluate this, we just started a Brain Initiative-funded project, where we will be implanting 8 patients with bilateral Percept PC neurostimulators with BrainSense Technology (Medtronic PLC) along with bilateral directional leads targeting the CM and the aGPi. Identifying physiological features in both nuclei can help us understand intersubject variability, as well as which nucleus does a better job at detecting tics, and which one at suppressing tics. This could reveal valuable information about the pathophysiology of this disorder and could guide the development and improvement of neuromodulation therapies for Tourette.

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Identifying sEEG Contacts with Auditory Perception and Speech Production Information: A Pilot Study

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Introduction: Brain-Computer Interfaces (BCIs) have shown promise for restoring communication to those who have lost this ability as a result of a neurological disease or injury. For those who have completely lost the ability to speak, the ultimate objective is to synthesize acoustic speech directly from brain activity associated with imagined speech [1]. One of the main challenges of designing a practical speech-BCI is the uncertainty about the brain regions and processes associated with imagined speech production. This pilot study examines stereo electroencephalographic (sEEG) data [2] and suggests that the vicinity of the auditory cortex and belts, previously believed to be predominantly associated with auditory perception, exhibit information relevant to imagined-speech BCI.

Materials, Methods, and Results: sEEG recordings were obtained from seven patients being monitored as part of treatment for intractable epilepsy at UCSD Health. The number of sEEG electrodes varied between 70-232 across participants and was solely based on clinical need. For the experiment, participants were presented with a short sentence on a monitor and simultaneously narrated via speakers. Participants were cued to overtly speak the sentence, followed by a cue to imagine speaking the sentence, while their voice was recorded simultaneously with the sEEG signals. The audio from the overt speaking trials was used to label the data as ‘speech’ from the onset to offset of the acoustic speech or ‘non-speech’ otherwise. The average onset timings and durations of the overt speech intervals were used to define surrogate ‘speech’ and ‘non-speech’ intervals for the imagined speech trials.

The channels in the vicinity of the auditory cortex and belts exhibiting large relative correlations between broadband gamma activity and audio recordings of the narrated sentences were identified as perceptual channels based on cross-correlation between the Hilbert amplitude envelopes of the audio file and the channel’s broadband gamma power [3]. Channels exhibiting correlations above two standard deviations ($p<0.05$) from the mean across all channels were marked as predominantly perceptual channels (40 out of over 800 channels).

For both overt and imagined speech trials, the signal energy of each perceptual channel was calculated in theta (4-8 Hz), alpha (8-12 Hz), beta (12-30 Hz), and broadband gamma (70-170 Hz) bands in 10-ms steps from 200 ms before the speech-onset to speech-offset. These features were used to train a causal logistic regression model and a 10-fold cross-validation analysis to predict speech activity [4]. While all perceptual channels had significantly above chance performance for overt, only 16 of the 40 perceptual channels exhibited performance significantly above chance for imagined ($p<0.05$).

Discussion: Despite the absence of auditory feedback, channels in or proximal to auditory cortex detected speech activity during imagined speech trials significantly better than chance. This is consistent with previous studies showing activation in the auditory cortices during imagined speech or imagined hearing, regardless of the presence of an auditory stimulus [4-6].

Significance: The results of this pilot study suggest that brain regions in or around the auditory cortex, may exhibit information associated with imagined speech production that could inform the development of refined speech synthesis models.

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A Functional Ultrasound Brain-Machine Interface: Real-Time Decoding of Direction and Task State

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Introduction: Brain-machine interfaces (BMIs) are transformative for people living with chronic paralysis, enabling them to control computers, robots, and more with only thought. However, state-of-the-art BMIs have shortcomings that limit user adoption. These include high invasiveness, small field of view, limited lifespan, and a need to calibrate daily. Functional ultrasound imaging (fUSI) is an emerging technique that can address these limitations[1,2].

Material, Methods, and Results: In this study, we demonstrate the first successful implementation of a closed-loop ultrasonic BMI (**Fig. 1A**). We streamed functional ultrasound data from the posterior parietal cortex of two rhesus macaque monkeys (**Fig. 1B**) while they performed memory-guided eye and hand movements. After a period of training, the monkeys were able to control up to eight independent movement directions using the BMI. We show that we can decode not only the intended movement direction, but also the current task state (fixation, movement planning, movement, and intertrial interval). We also present a method for pretraining ultrasonic BMIs using data from previous sessions (**Fig. 1C**). This enabled immediate and improved BMI control on subsequent days, even those that occurred months apart, without requiring extensive calibration. Finally, we have begun translating this ultrasonic BMI into non-invasive human applications taking advantage of a unique patient population with ultrasound-transparent skull replacements.

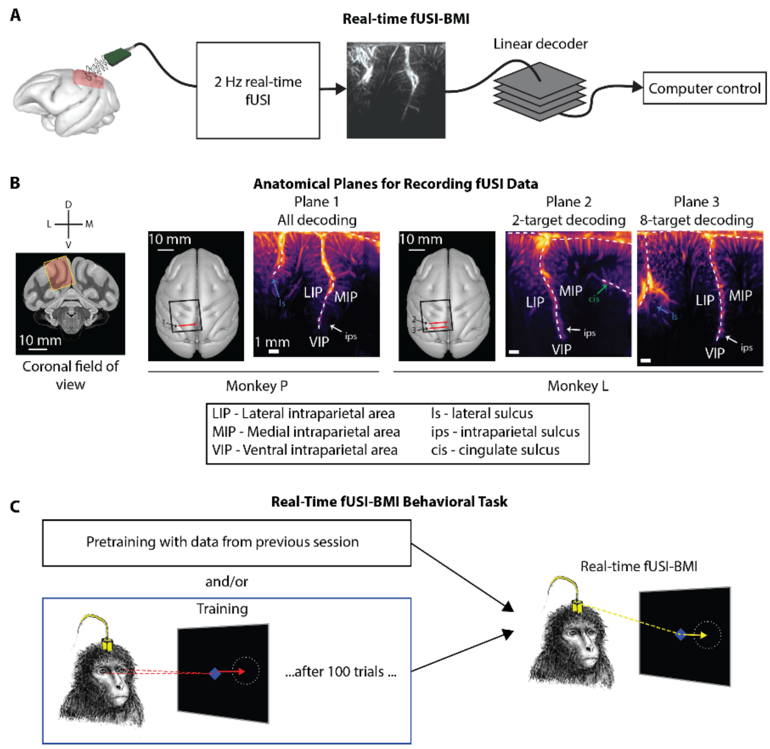

Figure 1: Overview of methods and results.

Discussion and significance: The contributions presented here demonstrate the first online, closed-loop ultrasonic BMI. It prepares for a next generation of BMIs that are less invasive, high-resolution, stable across time, and scalable to sense activity from large regions of the brain. These advances are a step toward fUS-BMI for a broader range of applications, including restoring function to patients suffering from debilitating neuropsychiatric disorders.

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Biological relevance of visual stimuli modulates the temporal binding window between ICMS and vision

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Introduction: Intra-cortical microstimulation (ICMS) of primary somatosensory cortex (S1) can elicit artificial tactile sensations in humans, but there has been little work on how the brain processes this non-naturalistic input in multisensory contexts. Understanding the timing necessary for visual and ICMS stimuli to feel simultaneous (the temporal binding window) is essential for a successful closed-loop brain-machine interface (BMI).

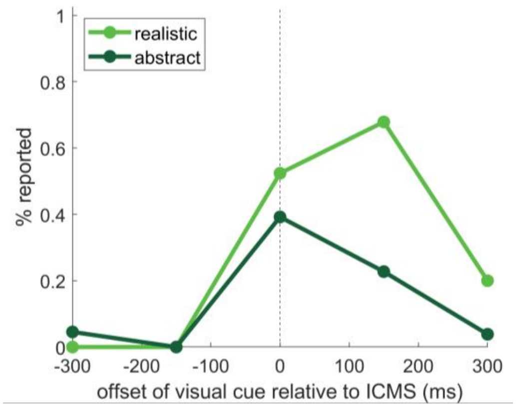

Figure 1. *Proportion of trials in which the participant reported visual contact and ICMS-evoked sensations were simultaneous, in two visual conditions.*

Material, Methods and Results: A tetraplegic patient implanted with 2 microelectrode arrays (Blackrock Neurotech) in S1 received single-channel ICMS (60 or 100 µA, 300Hz, 0.5s) while observing visual cues. Visual and ICMS stimuli were delivered at varying offsets from one another (0, 150 or 300ms). Visual cues, presented in virtual reality, were either abstract (a dot moving to the end of a line) or realistic (a robotic arm tapping a first-person-perspective human arm). The participant reported whether visual contact or ICMS-evoked sensations occurred first, or if they were simultaneous. Task performance was equal across visual conditions and was not affected by learning over time. The patient was more likely to perceive an order to the stimuli (vision before ICMS or ICMS before vision) in the abstract condition, whereas in the realistic condition the patient was more likely to perceive the stimuli as simultaneous (Fig. 1). Based on behavioral data, the participant experienced ICMS at a temporal lag relative to visual input, with a larger lag in realistic trials (~100ms) than in abstract trials (~50ms) (Wilcoxon sign rank test, $p<0.05$), despite more realistic trials being reported as simultaneous overall. Electrophysiological data was recorded during the experiment. During catch trials, in which no ICMS was applied, it was possible to decode baseline vs visual contact in both conditions, and generalize this decoder across conditions.

Discussion: The perceptual lag between visual and ICMS inputs indicates that ICMS is not well-integrated into a unified conscious experience of touch. Behavioral differences between visual conditions suggest that a more biologically relevant visual scene results in a larger temporal binding window between visual cues and ICMS. Visual content that more closely mimics biological touch allows the brain to better integrate ICMS inputs as part of a causal, multisensory environment. Additionally, decodable visual information in S1 indicates that S1 represents salient multisensory content in a context-independent fashion.

Significance: ICMS represents a potential method to restore touch and provide a closed-loop BMI to individuals with sensorimotor disorders. Uncovering how S1 encodes touch-related stimuli and how ICMS is interpreted in a multisensory context is necessary to understand uses and limitations of ICMS in real world environments.

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Inter-Stimulus Latency Jitter in RSVP Keyboard: Effects on Attentional Event-Related Potentials

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Introduction: It is well-established that sequential presentation of stimuli can affect measurements of event-related potentials (ERPs) from electroencephalograms (EEGs), particularly when the neurologic processing of subsequent stimuli overlap in time [1]. Prior work suggests that steady-state visual presentation of letter stimuli has the potential to obscure EEG-based measures of attention [2]. Despite this understanding, the vast majority of brain-computer interface (BCI) P300-based systems do not explicitly control for overlapping stimulus presentations. One possible solution to improve ERP measures in the presence of adjacent stimuli is to vary ("jitter") inter-stimulus latencies [1].

Material, Methods and Results: This study investigated interference of steady-state visual-evoked potentials (SSVEPs) with attentional ERPs in a P300-based BCI for communication, RSVP Keyboard. EEGs were recorded from 24 adults without SSPI (age 18-76) during three rounds of RSVP calibration/copy-phrase with letters presented at a rate of 5 Hz using python-based BciPy [3]. Three levels of range of stimulus jitter were applied in an attempt to attenuate overlap and SSVEP effects in ERPs: 1) conventional no inter-stimulus jitter; 2) ±50 ms; and 3) ±100 ms. A final 1 Hz calibration was completed in order to examine non-overlapping ERPs. Results showed significant N200 and P300 ERP attention effects (see Fig. 1; all p values < .001), as well as a significant reduction in noise (as assessed by the standard deviation of target ERPs) in both jitter conditions, relative to the no-jitter condition (both p values < .05). Classifier models from calibration runs were generated in BciPy using PCA pre-processing and a regularized discriminant [3]. However, there were no significant differences in classifier performance (AUCs or balanced accuracy), copy-phrase accuracy, or ERP attention effects between jitter conditions (all p values > .10). Approximately half of participants did not independently notice jitters, and there was no clear user preference for or against stimulus jitter. Supplementary analyses examined measures of attentional alpha attenuation.

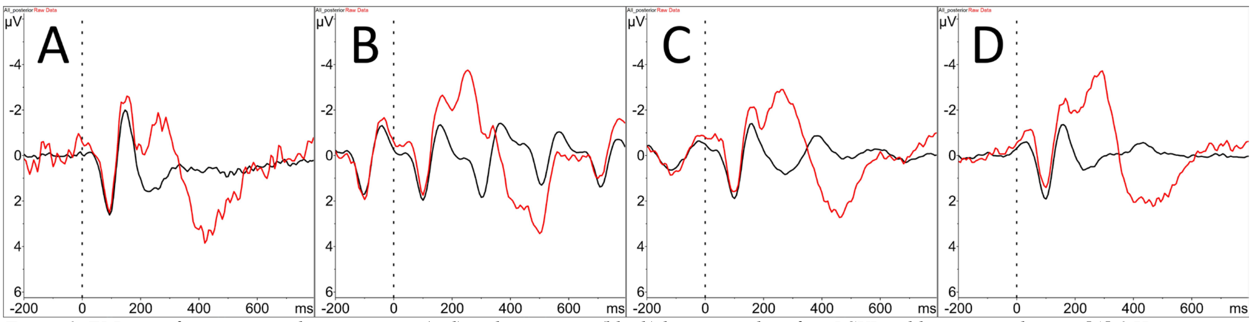

Figure 1. ERP waveforms averaged across target (red) and non-target (black) letter stimuli in four RSVP calibration conditions: [A] 1 Hz presentation with no stimulus jitter; [B] 5 Hz presentation with no jitter; [C] 5 Hz presentation with small jitter of ±50 ms; and [D] 5 Hz presentation with a large jitter of ±100 ms. Intrusion of the SSVEP signal is greatly decreased in conditions [C] and [D], compared to [B].

Discussion: Results suggest that even moderate stimulus "jitter" has the potential to improve measurement of attentional ERPs for BCI control. However, it is unclear how these jittered presentations might impact brain indices of attention in different BCI paradigms. Classifier performance was not obviously affected by the presence of the SSVEP, even with greater signal-to-noise (i.e., P300-to-SSVEP ratio). Overlapping stimulus processing does not seem to necessarily hurt ERP-based target classification, even though it appears to alter other EEG measures of attention (e.g., event-related alpha attenuation).

Significance: Jittered inter-stimulus latencies have the potential to improve BCI performance, especially as a relatively quick and imperceptible modification to extant designs.

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Should robotic limb control mimic the human body? Effect of control strategies on bionic hand skill learning

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Introduction: A longstanding engineering ambition has been to design anthropomorphic bionic limbs: devices that look like and are controlled in the same way as the biological body (biomimetic). Biomimetic-inspired design in human-machine interfaces is built on the (untested) assumption that biomimetic devices might allow users to recruit pre-existing neural resources supporting the biological body to assist device control, thereby enhancing device learning, automaticity, generalization, and embodiment. But are these assumptions that underlie biomimetic design valid? Here, we sought to compare biomimetic and non-biomimetic control strategies when learning to operate a bionic hand. As a striking alternative to biomimetic control, we used an arbitrary (non-biomimetic) control strategy, which should, based on the neurocognitive assumptions underlying biomimetic design, provide no direct benefits.

Methods: To assess bionic hand skill learning, we trained able-bodied participants (n=40) over 4 days (2-3 hours per day) to use a wearable EMG-based myoelectric bionic hand operated by an 8-channel EMG pattern recognition system (Figure 1). We compared motor learning across days and behavioural tasks for two training groups: biomimetic (n=20; mimicking the desired bionic hand gesture with biological hand) and arbitrary (n=20; mapping an unrelated biological hand gesture with the desired bionic gesture). After training, we assessed how well the learning would generalize to a new control mapping. We also tested a control group (n=20) that received no bionic hand training. To quantify the neural embodiment of the bionic hand, participants underwent functional MRI scans before and after training (1-week apart for the controls; 120 scans total). In the scanner, participants performed a visuomotor task that assessed visual and motor aspects of bionic hand representation.

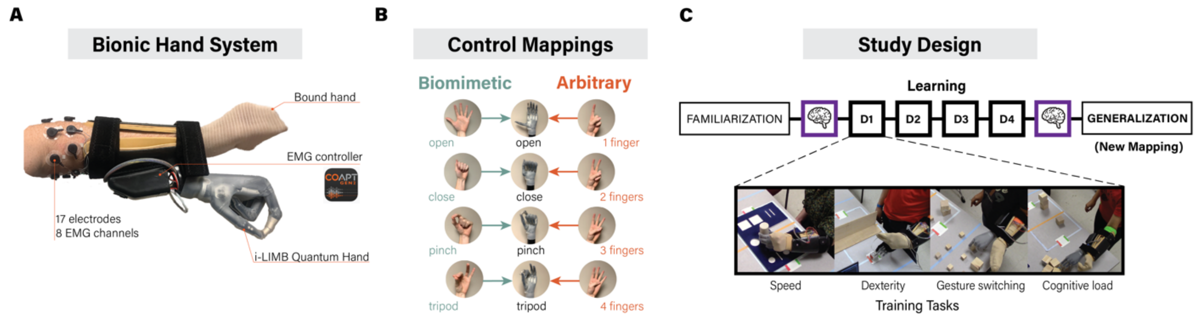

Figure 1. Experimental design of the study. (A) Bionic hand system. **(B)** The control mappings for biomimetic and arbitrary control strategies. **(C)** Experimental design each trained participant underwent. Brains denote when the fMRI scans took place pre- and post-training. D=day.

Results: Trained participants improved motor control, reduced cognitive reliance, and increase sense of embodiment over the bionic hand. Biomimetic control provided more intuitive and faster performance in the early stages of learning. However, when task difficulty was increased (complex gestures, dexterous grasping and gesture switching tasks), biomimetic users performed the same as arbitrary users. Further, arbitrary users showed increased generalization compared to biomimetic users. In the neuroimaging, trained participants showed training-dependent changes in visual and sensorimotor cortex related to different aspects of bionic limb control.

Discussion: It is a widely held assumption that control strategies designed to mimic the biological body might provide unique benefits to the user in terms of device learning, sense of embodiment, automaticity, and generalization. Contrary to this view, across a multitude of tasks, we observed few task advantages for biomimetic control. In summary, our findings suggest that biomimetic and arbitrary control strategies provide different benefits. The optimal strategy likely depends on training opportunities and user requirements.

Significance: Our findings provide a more balanced perspective of the cognitive advantages and limitations of biomimetic motor control. By challenging some of the core assumptions underlying biomimetic inspired design, our findings open up the potential for non-biomimetic control solutions for users.

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A non-invasive EEG-based Brain-Machine Interface for the control of myoelectric prostheses

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Introduction. Decoding brain activity is an ongoing research challenge with implications for the control of upper and lower limb prostheses [1,2]. This study represents a non-invasive Brain-Machine Interface (BMI) to control upper limbs and reports the classification performance of four different grasp movements realized by a myoelectric hand prosthesis (Myobock, Ottobock), modified to be controlled by EEG signals.

Material, Methods and Results. The experimental data were collected in three experimental sessions during which amputee and able-bodied subjects performed different grasp movements under two conditions: Motor Execution (ME) and Motor Imagery (MI). Two different methods based on the combination of the Common Spatial Patterns and Wavelet Decomposition techniques [3] and on an alternative approach using Riemannian Geometry were used to extract the features to be used as inputs to the classification algorithms employed to decode the EEG activity. The prediction performances of the system have also been tested with several combinations of electrodes and compared to the ones obtained by the original set of electrodes. The classification performances obtained by the six decoding algorithms are well above chance levels for all binary classification models with the best results obtained using the Support Vector Machines (SVM). For the four movements, there are almost no differences in terms of classification performance between the MI and ME conditions. In ME the performance of the able-bodied group is superior to the amputee group. Finally, a 2% drop in prediction performance is obtained when reducing the electrodes from 64 to 32 (Fig. 1).

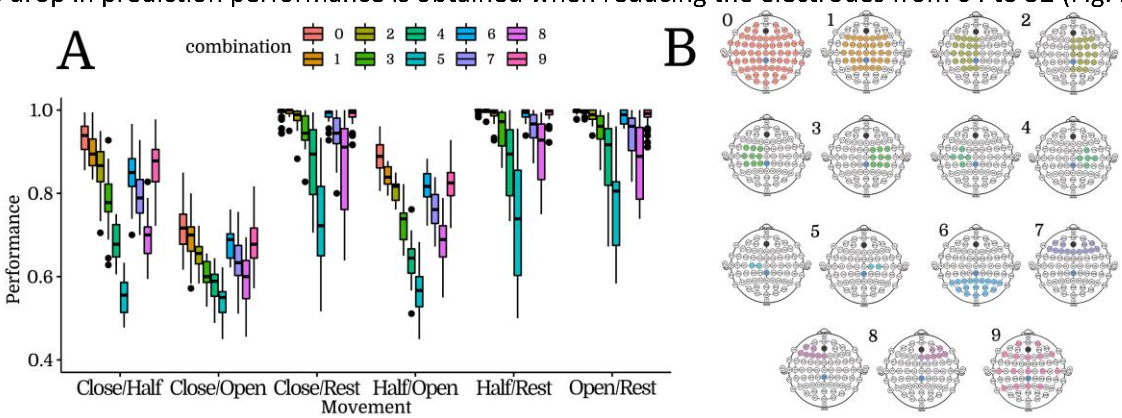

Figure 1 A. Comparison of the performance of the Radial Basis Function SVM for different combination of electrodes and for the six binary classification models. B. Original and nine different set of combinations of electrodes.

Discussion. Even though the EEG signal represents more abstract information about the brain activity compared to the signals obtained by invasive methods our results showed that it can be used to control hand prostheses. The amputee people can perform the movements with similar performance both in ME and MI conditions and the classification performances obtained with different algorithms and feature extraction methods are not significantly different.

Significance. This work gives a proof of concept for the use of a non-invasive BMI system dedicated to the control of prostheses, paving the way for developing a feasible system with a small number of electrodes.

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Mechanisms and Impacts of Brain-Computer Interface Fatigue in Children

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Introduction: Brain-computer interfaces (BCIs) can assist children with disability with communication, environmental exploration, and game play [1]. BCI progress is rapidly accelerating but has neglected pediatric populations [1,2]. Fatigue is a key performance factor [2,3] and a common side effect reported by patients and families within our pediatric clinical BCI program. This study aims to assess the effects of BCI operation on self-reported fatigue and explore previously associated electroencephalography (EEG) fatigue biomarkers, such as alpha bandpower changes [4], in children.

Materials & Methods: Thirty-five healthy children were recruited (median age 10 yrs, range 6-16, 19 females) for this randomized prospective cross-over study. Participants played a P300 or motor imagery (MI) computer game using an EEG-BCI in two sessions and attended a third video viewing session (control). Self-reported fatigue was measured using a 10-point visual analog scale before and after each session. EEG was measured in resting state periods before and after the task and analyzed for alpha bandpower. Preliminary statistical analysis was done using mixed modelling.

Results: Procedures were generally well tolerated with no serious adverse events. Headset discomfort was common (63%) but only precluded completion for one individual. Training classification accuracy for MI and P300 respectively were 59% and 93% (n=24). The P300 control scheme was associated with greater increases in self-reported fatigue compared to the control condition. MI paradigm fatigue scores demonstrated greater variability and the mean did not differ from controls (Fig.1A). The alpha bandpower tended to increase across the video and P300 sessions but decreased across the MI session. There were no significant differences in the alpha change between session types (n=13; Fig. 1B). Further alpha band analysis will be completed along with EEG entropy quantification.

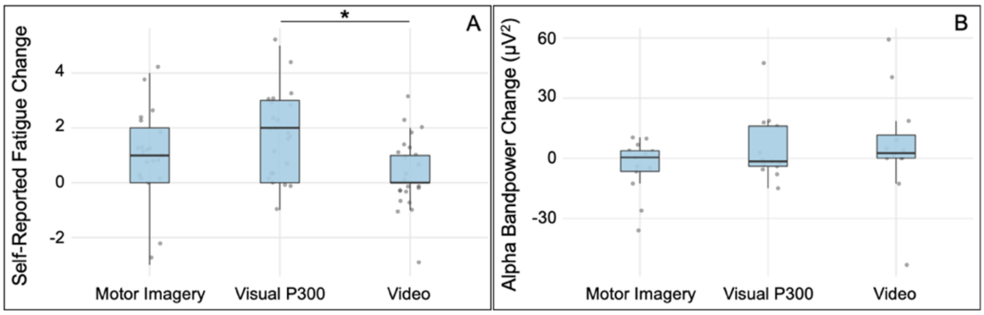

*Figure 1. A. Difference (post task – pre task value) in self-reported fatigue following a 30-minute BCI or video viewing task measured on a 10pt visual analog scale. B. Alpha bandpower (8-12Hz) difference in the resting-state period before and after the 30-minute BCI or video viewing task (post task – pre task). Plots show IQR and median. * p=0.005.*

Discussion: Fatigue is measurable in children performing common BCI paradigms. Preliminary data indicates that BCI may increase fatigue, with intensity varying across paradigms. It remains to be determined whether the alpha bandpower change will show any correlation with the self-reported fatigue values or changes in BCI performance.

Significance: This project provides a baseline understanding of BCI fatigue in children with potential to inform the design of pediatric BCI systems to meet the goals identified by children with disabilities and their families.

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Predicting User Goals Based on Simulated Brain-Computer Interface Inputs and Robot Sensor Data

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Introduction: Non-invasive brain-computer interfaces (BCIs) provide users with low-dimensional, low-throughout, and inaccurate signals [1,2], leading to difficulties in controlling the many degrees of freedom of a robotic arm. To improve performance, a BCI can be combined with autonomous assistance in a shared control architecture that leverages external sensor data to assist the user [3]. However, to provide this type of assistance, the system needs to understand the goal of the user. Goal determination can be done using an additional input interface (e.g., eye-tracking [4]), but this approach increases system complexity and restricts the user. As an alternative, we explore four algorithms for goal prediction that utilise a single stream of user inputs, and robot sensor data.

Material, Methods, and Results: We used previously collected data from an experiment where twelve participants were tasked with reaching one of five objects in a 3D environment with a robotic arm. We tested two existing algorithms [5] – Amnesic Euclidean (AE) and Euclidean with Memory (EM) – and two new methods – Input Angle (IA) and Input Distance (ID) – for continuously predicting the goal of the user (i.e., which object they wanted to reach). To control robot motion, participants supplied commands using a noisy joystick, the accuracy of which could be set explicitly. This joystick simulated a non-invasive BCI that output four discrete control commands [1,2]. By explicitly setting the accuracy of the interface, the algorithms could be directly compared without variable BCI performance being a confounder.

Predictions were made every 100 ms. AE predicted the object that was closest to the end-effector [5]. EM predicted the most likely object given the distance to each object from the current and starting positions [5]. Assuming the user wanted to move the end-effector directly towards their goal, IA predicted the goal based on the angle between the user input vector and the vector to each object. Similarly, ID predictions used an estimate of the distance that the end-effector would travel towards each object due to the input. At each time step, IA and ID predictions used the entire history of user inputs and end-effector co-ordinates.

Each algorithm was tested on data from successful trials where the interface accuracy was set to either 100% (N=302), 79% (N=303), or 65% (N=297), where 79% and 65% represent typical maximum and mean accuracies of four-class motor imagery BCIs, respectively [2]. Across all three levels of input accuracy, EM, IA, and ID accurately predicted the goal object in greater than 80% (median) of time steps within a trial, while the median proportion of accurate predictions produced by AE was significantly lower (two-sided Mann-Whitney U test, $p < 0.0001$).

Discussion: The high prediction accuracy of EM, IA, and ID showed that heuristic models of behaviour can be used to predict the goal of the user in a reaching task without the need for an additional interface, even when interface accuracy is relatively low. The significantly worse performance of AE demonstrated that the entire history of user inputs and end-effector trajectory should be used to perform predictions.

Significance: When operating a robotic arm using a BCI, predicting which object a user is trying to reach can be used to guide the end-effector, minimising the negative impact of BCI decoder errors on robot motion and making non-invasive BCIs more viable for robotic arm control.

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A feasibility study on the development of a movement related cortical potential based brain-computer interface for communication in patients with amyotrophic lateral sclerosis

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Introduction. Besides the implemented algorithms and hardware, a key component of a brain computer interface (BCI) is the brain signal used to control the external device. There are several brain signals that have been implemented such as evoked potentials e.g. the P300 signal, but also spontaneous potentials such as the movement related cortical potential (MRCP) [1, 2]. The MRCP is a slow cortical potential that arises during the preparation and execution of movements or only during movement imagination [3]. In contrast to the P300-based BCI, an MRCP-based BCI may provide with several advantages. The MRCP develops naturally without external stimuli and can be retrieved immediately without extensive practice. In this study, we investigated the feasibility of controlling an MRCP-based BCI speller. The aim was to quantify the morphology of the MRCP of individual subjects during a simple movement task either performed alone or in combination with the cognitive task of selecting letters presented as a visual cue.

Materials, Methods, and Results. Electroencephalography (EEG) signals from 10 channels (FP1, Fz, FC1, FC2,C3,Cz,C4,CP1,CP2 und Pz) were recorded from ten healthy volunteers (3 female and 7 male , 37 ± 13 years old) during a simple motor task (30 dorsiflexions - DF) and during a combination of a cognitive (spelling) and motor task guided by a visual cue (DF+spelling). The DF+spelling task comprised spelling two sentences with 14-15 letters per sentence presented to each subject in randomized order. To select the appropriate letter, the subject had to perform a dorsiflexion when the desired line and letter appeared. Between each sentence the subjects were allowed to rest for 1-5 minutes. The DF task was performed at the beginning and at the end of the session and served as the control MRCP. EEG signals were subsequently analysed offline; bandpass filtered between 0.05 to 5 Hz using a Butterwortth bandpass filter and segmented into epochs from 2s before to 2s after task onset. Eleven temporal features obtained from each trial by extracting the time and amplitude of the peak negativity of the MRCP and the slopes of different time intervals of the MRCP, including their variability were then extracted and used to compare the individual MRCPs for all conditions. A paired t-test with a Bonferroni correction was applied with significance level of $p=0.0045$.

The results showed that the extracted MRCP signals had the typical morphology for all conditions. Therefore, the additional cognitive task had no effect on the quality of the MRCP. With a threshold of $p=0.0045$, no difference was found between the DF and DF+spelling tasks. However, a significant difference was found for the variability of the late negativity of the MRCP when comparing the last DF+spelling task to all other tasks, indicating a possible adaptation and training effect. In addition, a decrease in amplitude was observed in the last DF task compared to the first DF task, which may have been induced by fatigue.

Discussion and Significance. Since the morphology of the MRCP and most of the extracted features did not show significant differences across tasks, the development of an MRCP-based BCI speller is possible and feasible. However, some aspects such as fatigue and adaptability need to be considered in future studies.

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Auditory High Entropy Response (A-HER): a new paradigm with high amplitude for Potential auditory-BCI application

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Introduction: Steady-State Visual Evoked Potential (SSVEP), for its high signal-to-noise ratio (SNR), is one of the most popular paradigms in Brain-Computer Interface (BCI)[1]. In contrast, Steady-State Auditory Evoked Potential (SSAEP), also known as Auditory Steady-State Responses (A-SSR), on the other hand, is challenging to use in BCI applications due to its poor SNR[2]. In this work, Auditory High Entropy Response (A-HER) is proposed with high SNR in the brain wave modulation for the potential non-visual BCI application.

In information theory, Shannon entropy is a measurement of the uncertainty of a sequence. By delivering high entropy sequence instead of the certainty stimulus sequence in A-SSR, A-HER can modulate brain rhythms in the prefrontal theta band, in which the effect of repetition suppression has been reduced greatly. A description of A-HER is introduced in Fig. 1(A).

Material, Methods and Results: 20 subjects were taken participated in the experiment with two sessions. In each session, there were 10 runs with the repeated auditory stimuli with frequencies of 0.5Hz, 1Hz, 2Hz, 5Hz, 8Hz, 10Hz, 12Hz, and 20Hz. Auditory stimuli were delivered with the fixed pure tone of 800Hz in session 1 for the A-SSR paradigm, and random tone selected a whole hundred pitch from 300-1200Hz in session 2 for the A-HER paradigm. As is shown in Fig. 1(B), the A-SSR paradigm with fixed tone stimulation in session 1 did not have a clear frequency response. By using the random tones in the A-HER paradigm instead of the fixed tune, the response would appear around the frontal theta band.

Significance: A new type of paradigm, named Auditory High Entropy Response (A-HER) has been proposed in this work. By using the high uncertainty stimulus sequence instead of the deterministic stimulus sequences, A-HER could effectively reduce the effect of repetition suppression for frontal theta band EEG modulation. With the high SNR, A-HER could ideal candidate for non-auditory BCIs, which also has the potential application of clinical sensory diagnosis and psychological research.

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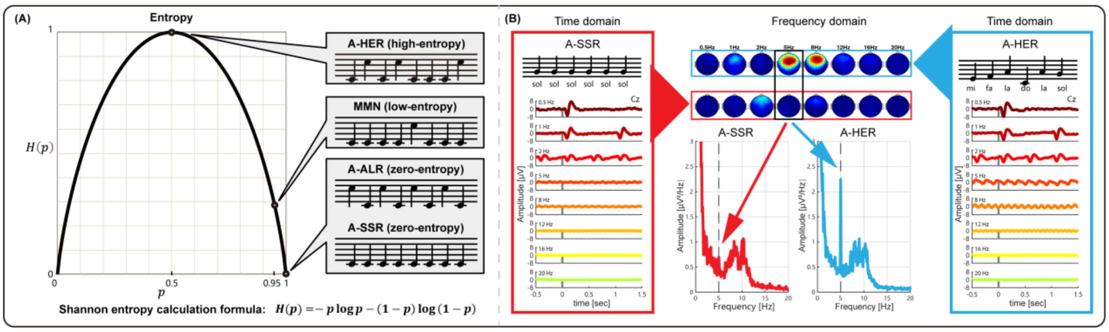

Figure 1(A) . The auditory stimulus sequence for A-HER, MMN, A-ALR, and A-SSR with their entropies. For A-SSR, with the prior probability p=1 for the standard stimulus, we have the entropy of the whole sequence H(X)=0. For A-ALR, with two types of stimuli come alternative, the whole sequence is also deterministic with the entropy H(X)=0. For MMN, the standard stimulus with a larger probability p=0.95, so the entropy of the whole sequence is also small H(X)=0.29. For A-HER, two types of stimuli come with the equal probability p=0.5, so the entropy reaches the maximum H(X)=1. Figure 1(B) . A-HER and A-SSR response in time domain and frequency domain. In the time domain, with the increase of stimulus frequency, the decay speed of the A-HER is slower than that of the A-SSR. In the frequency domain, the response would appear around the frontal theta band in A=HER but the A-SSR cannot.

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A large-scale study on the general public to assess and model the acceptability of BCIs dedicated to motor rehabilitation after stroke

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Introduction. While several meta-analyses have demonstrated the relevance of BCIs for improving motor recovery after stroke [1], these technologies are still barely used in clinical practice. We hypothesise that optimising the acceptability of BCIs could be used as a lever to increase the efficacy of BCI-based motor rehabilitation procedures, and thereby their clinical use. Indeed, a better acceptability will enable a reduction of anxiety levels and an enhancement of motivation and engagement in the procedure [2]. Both will in turn allow for more cognitive resources to be allocated to the task, thus favouring learning and, ultimately, motor recovery. To the best of our knowledge, so far only one study [3] has assessed the relevance of a BCI-based stroke rehabilitation procedure using acceptability measures among their primary criteria of efficacy. Most often, acceptability is only considered as an attribute of user satisfaction, itself being a dimension of user experience [4,5]. Yet, given its potential impact on BCI use, it seems important to study acceptability as an integral component. Thus, our objective is to rely on validated models depicted in other literature in order to design a first thorough model of acceptability specifically dedicated to BCI-based procedures for motor rehabilitation after stroke.

Material, Methods and Results: We designed a model of BCI acceptability (Fig.1A) based on the technology acceptance model 3 (TAM3) [6] and on the unified theory of acceptance and use of technology 2 (UTAUT2) [7] that assess acceptability in terms of perceived usefulness (PU), perceived ease of use (PEOU) and behavioural intention (BI). Then, we created a questionnaire based on our model in order to estimate its validity and to quantify the influence that each factor had on BCI acceptability. We collected a data sample of 753 respondents representative of the general public in France. We targeted the general public for two main reasons. (i) Due to the high prevalence of stroke, many of us are concerned, more or less directly, by stroke. (ii) Patients' acceptability is likely to be influenced by the opinions and attitudes of their close relatives (who are part of the general public) [8]. **Descriptive analyses:** Our results suggest that BCIs are associated with high levels of acceptability: PU (8.28/10 ±1.57), PEOU (7.17/10 ±1.57), BI (8.23/10 ±1.69). **Validity analyses:** Cronbach's α coefficient analyses revealed a satisfactory internal consistency of our questionnaire, i.e., the items used to measure each factor are mostly consistent and not too redundant (12/17 factors in [0.72;0.95], 4/17 in [0.50;0.62] and 1 = 0.97). Furthermore, a confirmatory factor analysis showed that the structure of the model is adequate. **Quantification analyses:** Regression analyses based on random forest algorithm revealed that BI is mainly driven by the PU of the system and by the perceived *benefits on risk ratio* associated with the technology. PU itself is mainly determined by the *scientific relevance* of BCIs and by PEOU. The main determinants of PEOU are *ease of learning* and *playfulness*. These results are depicted in Fig.1B.

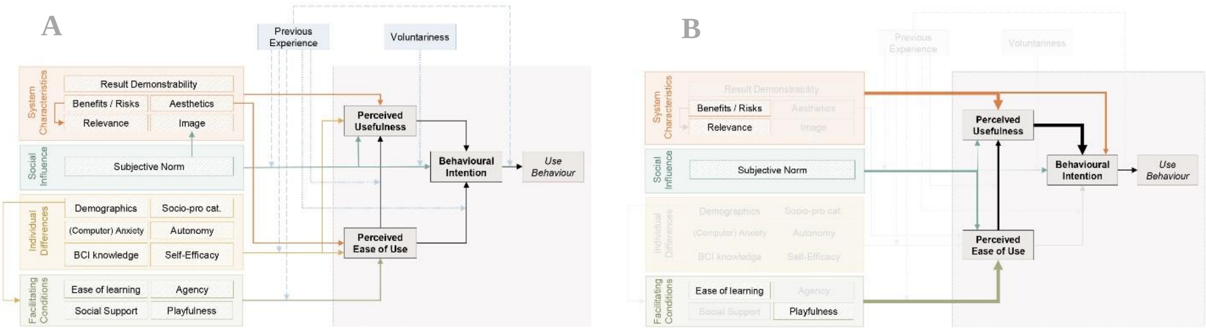

Figure: (A) Initial theoretical model of acceptability for BCIs dedicated to motor rehabilitation after stroke. (B) Final model highlighting the most influential factors based on our results (N=753 respondents from the general public)

Discussion: Our results suggest that beyond the *subjective norm* (i.e., perceived opinions of our close ones), several factors impact significantly BCI acceptability. Given the weight of the *scientific relevance* and *benefits/risk ratio*, it is of utmost importance to clearly inform the population. In addition, the impact of *playfulness* and *ease of learning* should encourage us to adapt the rehabilitation procedures to each patient. In order to refine this model, additional data should be collected, in particular with i) patients and caregivers; ii) persons from different cultures; and iii) in different contexts, i.e. for other use cases.

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Improving User Experience and Performance through Gamification of MI-BCI Training

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Introduction: Motor Imagery Brain-Computer Interfaces (MI-BCI) decode brain patterns associated with motor intentions into control commands for a variety of applications, bypassing traditional motor inputs. To use these systems, the user must produce identifiable and stable MI patterns [1], which requires multiple training sessions in a lab. However, MI-BCI training protocols are often repetitive and suboptimal as some users remain incapable of BCI control. This problem, known as **BCI illiteracy/deficiency** [2, 3], has been related to psychological and cognitive factors such as motivation and attention [1, 4]. While some studies have tried to improve users' MI skills and BCI performance through enriched feedback [5] or motor priming [6], a unified protocol that considers various aspects of user training has not yet been introduced.

Potential solutions: The current study aims to develop a more user-centered MI-BCI training protocol by implementing principles from human-computer interaction and game design. Through a systematic review, we examine how gamification of user training can improve user experience and BCI performance. Here, gamification refers to the use of game elements such as interactive objects, goals, and rewards, which can make BCI training more engaging, motivating, and effective [4, 7, 8]. A potential platform for such a BCI training game is virtual reality (VR). Not only does VR offer richer, immersive feedback during BCI training, it can also embody the user into a virtual character, giving them more agency over virtual movements performed with the BCI [8, 9]. We discuss how virtual environments have been used in MI-BCI training in combination with gamification, and introduce empirical studies that can further incorporate and test a gamified VR MI-BCI training protocol.

Significance: An overview of effective design principles for MI-BCI training can provide future BCI researchers and developers with a framework for creating more engaging and effective protocols that reduce the BCI inefficiency problem and accelerate the technology's mainstream adoption.

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The detection of *Windows of Consciousness* in locked-in patients

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Introduction: In 2020, Kübler suggested the search for *windows of consciousness* (WoC) to increase the probability of establishing BCI-based communication with patients suffering from the complete locked-in syndrome (CLIS) [1]. Interestingly, some brain activity patterns which were found to be related to high BCI performance in CLIS patients [2] – which might indicate the existence of WoC – already fluctuate in patients with classical locked-in syndrome (LIS), thus before they enter CLIS [3]. Combined with known fluctuations in BCI accuracy in ALS patients more generally [4], this may imply the existence of WoC in LIS-patients. To detect WoC, we decided to investigate resting-state recordings preceding BCI sessions with regard to two neural measures of consciousness. We chose 1) the *Lempel-Ziv complexity* (LZC) which is said to indicate the information-richness of the current conscious experience [5] as well as 2) the *power-law exponent* (PLE) that numerically expresses the brain's arrhythmic activity [6]. The PLE thereby is, as elucidated in the *temporo-spatial theory of consciousness*, a measure for the *temporal nestedness* of the different intrinsic neural timescales at play – shown to be related to arousal [7].

Materials, Methods and Results: To detect WoC in LIS-patients, we analyzed resting-state EEG data, recorded prior to the use of a P300-based tactile BCI in the same session from a single locked-in ALS patient. We explored potential systematic relationships between the outlined measures of consciousness (LZC, PLE) with the respective BCI online accuracy achieved. We were able to show strong correlations between these metrics and the accuracy reached with our tactile BCI [8] (see Figure 1).

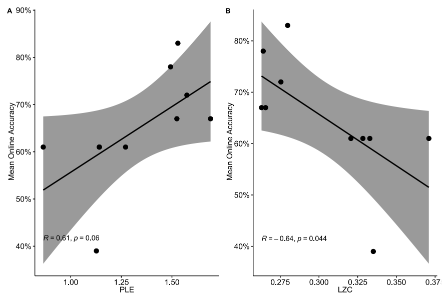

Figure 1. Pearson correlations between the power-law exponent (PLE) respectively Lempel-Ziv complexity (LZC) and the online accuracy reached with a tactile P300-based BCI.

Discussion: Our results suggest a relationship between states of consciousness in LIS-patients, as determined by the outlined metrics, and the online accuracy of a tactile P300-based BCI. Though some of the correlations reached significance, these first results should be validated on a substantially larger data set.

Significance: The detected relationship could be used to infer WoC in (C-)LIS-patients, i.e., the optimal time periods to initiate BCI-based communication to increase BCI accuracy.

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Classifier-based latency estimation for covert attention ERP decoding

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Introduction: Brain Computer Interfaces can restore communication for patients suffering from extreme motor disabilities. The most commonly used BCI in communication settings is based on the visual event-related potential (ERP). Here, the user attends to out of several flashing targets, and each time it is flashed, an ERP is generated which in turn can be gauged by EEG (electroencephalography). Traditionally, effective communication can only be achieved when the user directs their gaze to the intended target to select it [2]. For applicability across multiple different patient groups, the interface should not require directing one's eye gazen, since this ability might be impaired. The performance gap between gaze-dependent and gaze-independent operation of a visual ERP speller paradigm interface can partially be explained by differences in P300 ERP component latency jitter. We propose a new classifier-based latency estimation approach for latency correction which improves covert attention performance.

Material, Methods and Results: A pilot study with healthy participants (N=8) was carried out using a stimulation interface resembling the Hex-o-Spell [2] interface. Data was recorded in three distinct settings: overt attention (the participant was instructed to gaze at the cued target), covert attention (the user was instructed to gaze at the center of the screen) and split attention (the user was instructed to gaze at another target). The classifier-based latency estimation algorithm [1] was enhanced using cross-validation and a time-invariant, regularized linear classifier [3] for accurate single-trial latency estimation. Classification performance (ROC-AUC score) was analyzed with and without latency estimation. The analysis shows a significant increase in performance for covert attention and no significant difference in performance for overt and split attention.

Discussion: The improvement in covert attention decoding is mainly due to the compensation of jitter of the P300 component. Improvement in other attention settings is not observed since the P300 component, while being the ERP commponent with the highest amplitude, does not convey the most discriminatory information in these settings. Future work should focus on developping a multi-component approach.

Significance: Eye motor disabilities, ranging from discomfort while gazing at presented targets for a longer period to partial or complete ophtalmoplegia are common in patients suffering from ALS, MS, stroke or Locked-in Syndrome by other causes. A gaze-independent communication interface can allow patients to effectively communicate.

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A shared-control framework for BCI control of various effectors: towards home-used BCIs

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Introduction: Despite promising progress in ongoing clinical research in BCI, very few systems allow daily use outside the laboratory. Several shortcomings, in terms of device reliability, safety, portability and ease of use, still need to be addressed to enable home-use. In this context, an implantable BCI technology was developed [1], aiming to enable a person with quadriplegia to control various effectors in a semi-assisted shared-control framework based on proximity sensors [2].

Materials, methods and Results: The shared-control framework consisted in a combination of an ECoG-based BCI system and an external Time-Of Flight (ToF - ST-VL53L1X) sensor-based solution located on the effectors (Fig. 1). ToF sensors and control module constantly monitor the local surroundings in order to localize near objects/obstacles and progressively take control over the BCI system to assist the user. Preliminary experiments have been conducted with one tetraplegic participant as part of "BCI and Tetraplegia" (NCT02550522) clinical trial. Reach-and-grasp with a robotic arm and wheelchair driving tasks have been performed within this shared-control framework, and compared to their BCI-only execution. BCI decoding and sensors processing module have been integrated on a power wheelchair allowing the participant to drive freely using a fixed BCI model. A Kinova JACO arm allowed performing the reach and grasp task.

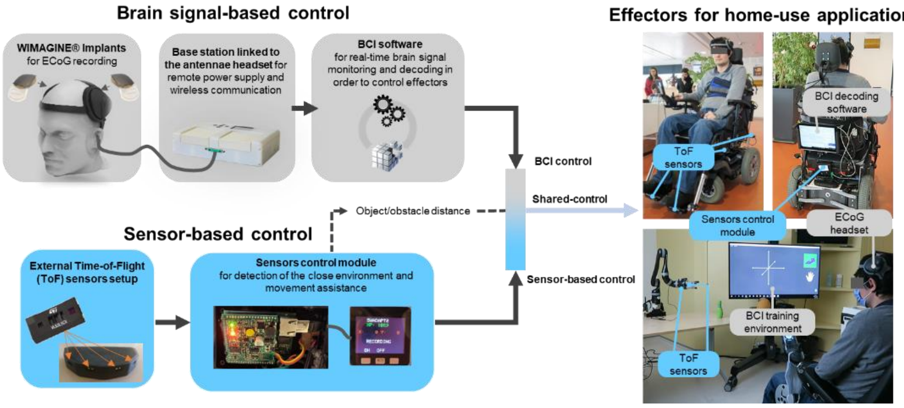

Figure 1. Schematic of the shared-control framework

A first proof of concept of 2D shared-control wheelchair driving was performed, showing the efficiency of the combination of BCI and sensor-based control compared to a BCI-only system, in terms of number of collisions and speed of execution. A significant reduction of the number of “mental commands” sent by the participant to perform the tasks was also observed, indicating a decrease of mental load using shared-control solution. 2D semi-assisted grasping was also demonstrated. The success rate was increased with shared-control compared to BCI-only.

Discussion and perspectives: In order to further evaluate the efficiency of the proposed solution, more experiments will be necessary in various use cases. Different strategies of fusion between both types of control are to be explored. Finally, hardware and software platforms will also need to be optimized to allow a better integration for home-use. The goal is to allow a faster and more accurate execution of tasks in a secure and robust way while leaving a “natural” control to the user.

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Randomized pilot study: BCI with FES motor priming to enhance the effect of physical therapy

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Introduction: Priming is a type of implicit learning where exposure to one stimulus causes a an altered response to another stimulus [1]. While the effect of Brain-Computer Interface (BCI) has been attributed to motor priming, it has not been previously explored whether it can improve the effect of a subsequent physical therapy. In this study we explored the effect of Brain Computer Interface guided Functional Electrical Stimulation just prior to hand therapy on the motor and neurological outcome.

Materials, Methods and Results:
Ten people with subacute Spinal Cord Injury (SCI) were randomly assigned to intervention and control groups, with 5 participants in each group, each receiving 20 sessions. The intervention group undertook 30 motor attempt guided BCI to control Functional Electrical Stimulation (FES) applied to the hand muscles of the dominant hand (refer [2] for more technical details). This was immediately followed by 30 min of conventional hand therapy. The control group received 40 min of conventional hand therapy. The outcome measures were changes in Manual Muscle Test (MMT), range of movements (ROM), latency of somato-sensory evoked potential (SSEP), event related desynchronisation (ERD) and the ratio between eyes opened and eyes closed EEG power (EC/EO).
Both groups showed improvement in MMT and ROM and a decrease in SSEP latency but there were no statistically significant differences between groups. EC/EO increased in the treatment group but decreased in the control group. ERD laterality was preserved in the intervention group only (Fig 1), while ERD in the control group is shifted towards the parietally occipital regions.

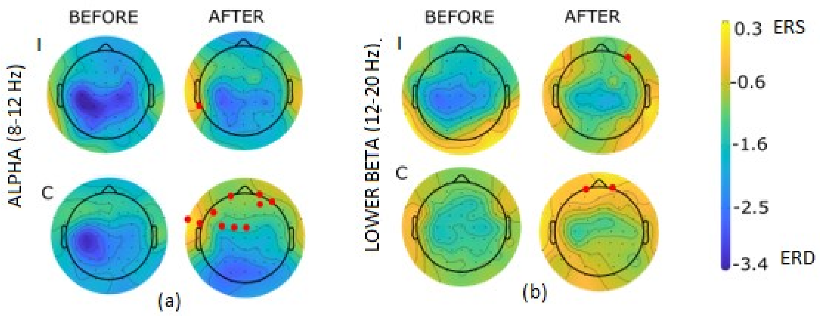

Fig. 1 . Event related synchronisation (ERS) and desynchronisation (ERD) before and after 20 sessions in the intervention (i) and control group (C) in a) alpha and b) beta 12-20 Hz. The red dots show statistically significant changes.

Discussion:
The duration of BCI FES in this study might have been too short, and the number of participants too small to notice a significant effect of motor priming on motor recovery. However, the intervention group preserved a contralateral cortical activity during motor attempts and increased EC/EO ratio, which is a measure of thalamic response to external sensory stimuli, that could decrease following SCI, being indicative of a risk of developing neuropathic pain [3].

Significance:
In clinical settings, BCI is delivered as an adjunct to standard therapy. Their interaction should be explored in order to maximize the cumulative effect of both therapies.

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Validation of an Automated EEG Artifact Removal Tool for Eye Movement and Muscle Artifacts

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Introduction: Automated artifact removal is a crucial step for brain-computer interface (BCI) systems. Maddirala & Veluvolu have developed an automated method to eliminate eye-blink artifacts for single-channel applications [1]. The purpose of this work is to extend this method to (a) be suitable for multichannel applications; and (b) test its performance in removing eye movements and muscle artifacts by computing its EEG quality index (EQI) [2].

Materials, Methods and Results: The multichannel artifact removal tool was implemented in Python 3.9.12 and has been made publicly available [3]. Resting-state EEG, eye movement, and muscle artifacts were extracted from the Temple University Hospital EEG Artifact Corpus (v2.0) dataset [4]. EEG traces were filtered with a 4th order band-pass digital Butterworth filter (f_c = 1 and 30 Hz). The filtered traces were then processed with the artifact removal tool (i.e., artifact-free data). The EQI was compared between the artifact-free and filtered traces. Filtered resting-state traces were considered as the reference for the EQI. Statistical analysis of the EQI was performed between the artifact-free and filtered traces by means of a paired one-tailed t-tests.

The artifact removal tool reduces eye movement and muscle artifacts in the EEG compared to just filtering (Fig. 1.A). EQI shows an increase (i.e., cleaner data) in most metrics, except zero crossing rate (ZRC) and kurtosis; the increase is more prominent in frontal channels (Fig. 1.B). Statistical analysis shows a significant increase in EQI ($p < 0.05$) for Fp1, Fp2, and T1 for eye movements, and Fp1, Fp2, F3, F4, P4, O1, T1 for muscle artifacts, respectively.

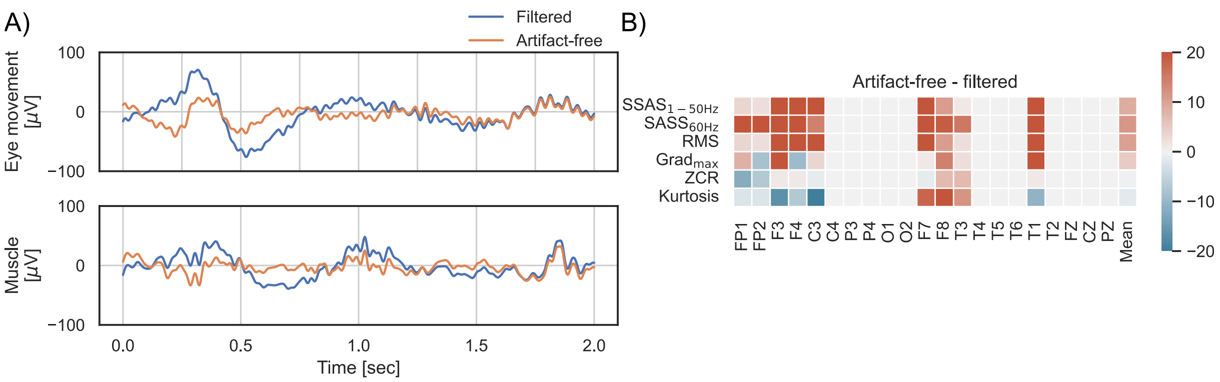

Fig. 1. A) Representative EEG traces showing eye movement (top) and muscle (bottom) artifacts. The filtered (blue) as well as the artifact-free (orange) traces are shown for channel Fp1. B) Representative EEG quality index heatmap showing the increase in quality comparing artifact-free vs filtered data for an eye movement artifact (higher is better).

Discussion: The artifact removal tool reduces eye movement and muscle artifacts but also affects some EQI metrics (e.g., ZRC and kurtosis). Further analysis should evaluate performance of machine learning classification and use of computational resources to test the suitability of the tool for online applications.

Significance: The updated automatic artifact removal tool presented is a viable solution for reducing eye movement and muscle artifacts.

Acknowledgments: We would like to thank ACHRI and NSERC CREATE for the funding of this work.

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Combining EEG and switch input in RSVP Keyboard

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Introduction: RSVP Keyboard is an EEG-based typing interface for people with severe speech and physical impairments (SSPI). It combines event-related potential and language model (LM) evidence to inform the characters presented to the user and selected for typing [1]. Here we describe Inquiry Preview (IP), a new RSVP Keyboard feature incorporating switch input as an additional control signal, and present results from pilot testing. This hybrid configuration may improve performance or user experience (UX).

Material, Methods and Results: Rapid serial visual presentation in RSVP Keyboard is divided into inquiries, typically of 10 characters. Characters in the first inquiry after a selection are those the LM identifies as the most likely targets given the previously typed string. Character probabilities are updated after each inquiry via Bayesian recursion until one character reaches a decision threshold. In IP mode, the user sees a box containing a preview of the characters in the upcoming inquiry. They can then activate a switch to either confirm that the target is included (causing the probabilities of included characters to increase and the inquiry to be presented to gather EEG evidence), or skip the inquiry if the target is not included (causing character probabilities to decrease). IP is also available without switch input.

Thirty-one participants without SSPI were recruited for pilot testing; 11 were excluded due to low calibration AUC (< 0.70; n=7) or poor EEG quality (n=4), leaving 20 included in data analysis (age 47.6 ± 19.20 years). After calibration, each participant completed copy-spelling tasks and a UX questionnaire. They copied 4 5-letter words under each of 4 conditions: standard RSVP, IP only (no switch input), IP with switch to confirm, and IP with switch to skip. Condition order was counterbalanced. Each condition included two “easy” words (in which all targets appeared in the first inquiry) and two “hard” words (in which one target did not appear until the third inquiry or later), selected at random. In the IP conditions, the preview was shown for 5 seconds or until switch activation, whichever came first. Stimuli were presented at 5 Hz, and the decision threshold was 0.80. If the threshold was not reached after 8 inquiries, the system selected the character with the highest probability based on combined LM, EEG, and switch evidence.

Typing accuracy and correct selections per minute (cspm) for each condition are summarized in the figure. Kruskal-Wallis tests revealed statistically significant differences between conditions for cspm but not for typing accuracy. Switch hits per selection averaged 3.8 for IP with switch to confirm and 0.4 for IP with switch to skip. In general, standard RSVP was the most preferred condition, followed by IP with switch to confirm. Narrative feedback revealed wide variety in opinions about the advantages and disadvantages of IP and switch input.

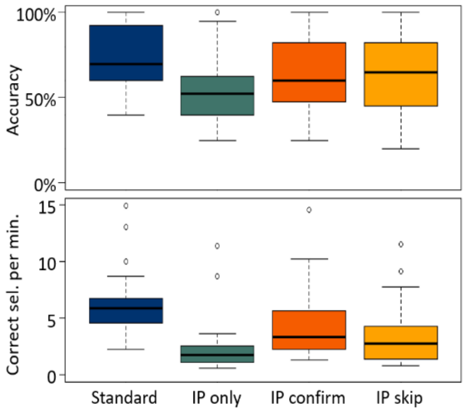

Figure: Typing accuracy and correct selections per minute by condition.

Discussion: The novel Inquiry Preview feature effectively integrated switch and EEG input in RSVP Keyboard, but did not increase typing accuracy or speed. Some participants preferred the user experience of an IP condition even if another condition was faster or more accurate. Outcomes may differ for users with SSPI.

Significance: BCIs with customizable interfaces may better adapt to user needs and preferences.

Acknowledgements: This work was supported by NIH R01DC009834.

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The effect of artificially created sensory feedback on motor cortex activity during task performance

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Introduction: Intracortical microstimulation (ICMS) of the human somatosensory cortex can evoke localized sensations on a person's own paralyzed hand [1] and can significantly improve the control of a brain-controlled prosthetic arm [2]. Under normal circumstances, there is a direct interplay between naturally evoked touch and motor control; where ongoing sensory input modulates motor cortex activity, causing complex patterns of inhibitory and excitatory responses. Here, we investigate whether artificial touch (created via ICMS) could have a similar effect on motor cortex activity. If this is not the case, we expect that the neural communication of ICMS reflects a simple additive relation, where increasing total stimulation charge will have increasingly excitatory effects on motor cortex activity. If it is the case, we expect to observe more complex parameter-dependent effects, suggesting that artificial touch may engage circuits that are involved in the processing of natural touch.

Material, Methods and Results: All experiments were conducted with two participants that had tetraplegia and intracortical microelectrode arrays implanted in their somatosensory and motor cortices (Blackrock Microsystems, Inc.). First, we assessed the effects of ICMS on motor cortex activity. To do so, we presented a participant with ICMS trains of various amplitudes (40, 60, 80 μA) and frequencies (50, 100, 200 Hz), while they passively watched a movie. Next, we investigated the effect of ICMS while participants attempted a motor task. To create a realistic and engaging context for these repetitive experiments, participants observed a Guitar Hero-like game while receiving ICMS. The game provided intuitive visual cues synced to musical notes in a song to indicate the timing of specific motor actions (full grasp, or individual finger movements). In both experiments, we compared the firing activity in the motor cortex prior to and during ICMS. We found that higher stimulation amplitudes linearly increased the global population activity in the motor cortex. However, frequency had a different effect. Although 50 Hz stimulation had a largely excitatory effect on the motor cortex, stimulation at 200 Hz had a predominantly inhibitory effect, while 100 Hz stimulation had mixed effects depending on the electrode. The excitatory effect of stimulation at 50 Hz was clearly visible during both motor task performance and at rest. Despite these prominent effects on motor cortex activity, preliminary results from one participant show that offline decoding of three individual fingers is possible (89% accuracy) in the presence of 50 Hz ICMS.

Discussion: Our results show that ICMS can have stimulus-dependent effects on motor cortex activity. We aim to elucidate these effects in future research in which we provide (in)congruent ICMS feedback while participants play a bidirectional brain-controlled version of our Guitar Hero game.

Significance: We show that ICMS cannot only be used to create an artificial sense of touch during motor control but can also modulate motor cortex activity in a stimulus-dependent way, similar to natural touch.

Acknowledgements: We would like to thank our magnificent participants, N. Copeland and Mr. Dom, for their participation in this study. This study was supported by the National Institute for Neurological Disorders and Stroke (U01 NS123125) and the Dutch Research Council (NWO Rubicon: 019.193SG.011).

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Pediatric Brain-Computer Interface (BCI) Participant Predictors and Experiences: Learnings from Year 1 of a Registry Project

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Introduction: Recent studies have demonstrated that children with severe physical disabilities can successfully control non-invasive brain-computer interface (BCI) systems [1,2]. There is a present need for translational research to improve the BCI user experience for children with physical disabilities, as well as evidence to inform guidelines for identifying suitable pediatric BCI candidates [3]. We have established a local research registry to (a) describe the experiences and engagement of children with physical disabilities and their-caregivers participating in the Glenrose Rehabilitation Hospital's BCI Program and (b) determine the relationship of clinical characteristics with participant experiences and engagement using BCI. Here, we present an overview of this ongoing project and summary of early findings.

Materials, Methods, and Results: Participants: All BCI Program participants aged 5-18 years and their caregivers were invited to take part in this study. All child participants were patients with a severe physical disability, defined as nonambulatory and with minimal functional hand use, and were part of a clinical program at a tertiary rehabilitation hospital in Edmonton, Alberta, Canada. Measures: To describe children's activities and participation, caregivers completed the PEM-CY at baseline and after BCI Program participation. Engagement during BCI sessions was assessed using the PRIME-SP and PRIME-P, respectively. After participating in the BCI program, children and their caregivers each completed a BCI Experience Survey. To characterize body functions and structures, study staff collected information from medical records, aligned with National Institute of Neurological Disorders and Stroke (NINDS) common data elements (e.g., the child's diagnosis; MRI characteristics; motor function; attention; language and communication; behaviour and mood; cognition and neurodevelopment; vision; and hearing). Results: To date, three individuals have enrolled in the project, with seven more expected by July 2023. Characteristics of the enrolled participants will be described as well as preliminary participation, engagement, and experience outcomes.

Discussion: This project will inform the systematic description of unique pediatric BCI participants and experiences. We anticipate that this project will lead to improved identification and characterization of potential participants for clinical programs and subsequent research studies.

Significance: This study will provide insight into characteristics of a pediatric population using BCI and knowledge to improve children's experiences using BCI.

Acknowledgements: We thank the participants for their hard work and insights. This work was generously funded by the Glenrose Rehabilitation Hospital Foundation.

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Characterizing Neural Representation and Sleep Architecture in Early Motor Sequence Learning Using a Chronic Neural Interface in Patients with Parkinson's Disease

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Introduction. The neural encoding of motor sequences over prolonged practice and consolidation of the corresponding memories during sleep are poorly understood in Parkinson's (PD) patients and healthy subjects alike. This is due to low spatiotemporal recording resolution and difficulties separating learned neural encoding changes from changes in neural activity as a byproduct of changing behavior. Our solution: (1) Use chronic multisite neural implants to record high spatiotemporal resolution local field potentials (LFPs) from the motor control network of PD patients while they practice typing two sequences for multiple days on (2) in-house custom equipment that precisely captures movement.

Methods and Results. Five PD patients were implanted with chronic, multisite bidirectional implants (Summit RC+S), with one quadripolar lead over motor cortex and one quadripolar lead in the basal ganglia (subthalamic nucleus or globus pallidus).

We recorded neural activity while patients performed a 5-day typing task and while they slept each night after the task. Each day, patients practiced typing sequences S1 and S2 in response to visual stimuli. An in-house keypad captured precise movement onset times using proximity and force sensors. A photodiode and additional eeg monitor (used to detect neurostimulation transients) soldered to the keypad motherboard allow for alignment of movement data with the visual stimuli and neural interfaces respectively. Patients demonstrated learning across days.

To assess pre-movement sequence-specific neural activity for learned sequences, we compared Day 4 neural activity for S1 vs. S2 during the 200ms prior to the onset of sequence execution in our first patient. Ridge classifiers trained on oscillatory power of dorsal STN (dSTN) (65.1%, $p = 0.001$), but not ventral STN (vSTN) (53.8%, $p = 0.21$) or M1 (50.0%, $p = 0.50$), predicted the identity of the upcoming sequence better than chance. Shuffling any frequency band largely decreased dSTN decoding accuracy; shuffling gamma caused the greatest drop (alpha: -12%, beta: -15%, gamma: -24%).

In our preliminary sleep analysis, we built a model to classify sleep stages using neural data and built spindle, slow oscillation (SO), and replay detectors. Early results suggest there is more spindle-SO coupling during sleep after the task relative to the null distribution and that spindles occur predominantly during slow wave sleep.

Discussion. Our early results show that single-trial classification on dSTN alpha, beta and gamma, collectively, can predict the identity of an upcoming movement sequence before movement has begun, suggesting dSTN may encode a motor planning or sequence-specific initiation signal for learned motor skills in PD patients. The failure of M1 activity to predict identity of a planned sequence is consistent with recent findings that M1 does not represent sequence identity, a high-level movement property, in healthy subjects either [1]. Our initial sleep analysis results show learning-related changes consistent with other work [2]. Our forthcoming analysis on additional behavioral epochs, sessions, patients, and treatment conditions (DBS ON) will help define a systems neurophysiological framework for understanding motor sequence learning, representation and offline consolidation in PD.

Significance. This is the first, that we know of, electrophysiological investigation of the role of the cortico-basal ganglia motor control network in human multi-day dexterous motor sequence learning at sufficient spatiotemporal resolution and the first electrophysiological investigation of prolonged motor sequence learning in PD at *any* spatiotemporal resolution. We provide evidence that low frequency aggregate neural activity can provide useful information for BCI decoders for hand movement.

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Fingermapping in Sensorimotor Cortex with ECoG

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Introduction: Although a somatotopic organization between limbs have been suggested in sensorimotor cortex for a long time, a somatotopy in M1 (primary motor cortex) for individual finger movements is still under debate [1]. That's mainly because of overlapping activations in M1 for different finger movements, which make it difficult to uncover any possible somatotopy [1, 2]. However, in a recent fMRI study from our lab, Schellekens et al. [1] showed that Gaussian population Receptive Field (pRF) models [3] can be applied to the sensorimotor cortex to reveal the somatotopy in finger representations. In this study, we repeated the same experiment with ECoG to explore whether pRF model reveals any somatotopy in that region with direct brain recordings as well, which is very crucial for further BCI applications with finer capabilities.

Material, Methods and Results: We analyzed data from 8 subjects implanted with high-density ECoG electrode grids for epilepsy monitoring. We executed the same task in [1] and used dataglove to mark the finger movements. After electrode localization [4], the electrodes in the sensorimotor cortex from all subjects were projected to the same 2D cartesian surface [5]. We followed the similar procedure in [1] to fit pRF model on high-frequency band (HFB) power; however, we used another gaussian function to reflect temporal aspect of the ECoG data, instead of the hemodynamic response function for fMRI. Obtained somatotopic maps of the electrodes indicating pRF centers and y-coordinates of the electrodes on the common surface are shown in *Figure-1*. In the postcentral gyrus, a somatotopy was found as indicated with a positive slope in the regression line (Fig-1a, $p < 0.05$). In the precentral gyrus, the electrodes were more spread due to inter-subject differences in the electrode coverages. Therefore, the electrodes were split into 2 clusters, and somatotopy was found in both clusters (Fig-1b, $p < 0.05$).

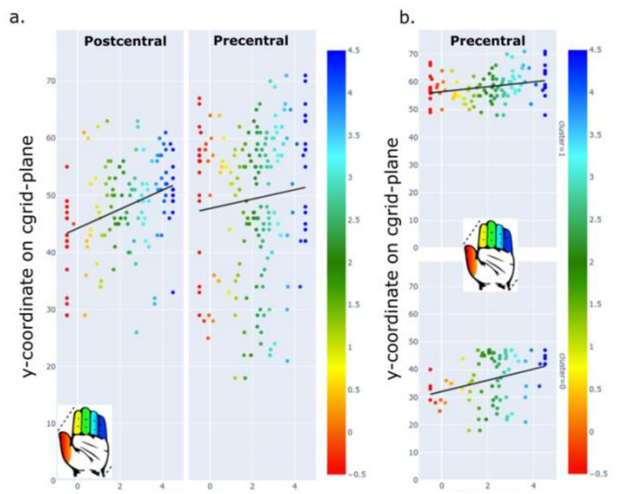

Figure 1. Somatotopic maps with linear regression. *Electrodes from all subjects whose HFB activity are predicted significantly during flexion movements of the fingers (corrected p-val < 0.05) are projected to a common cartesian grid [5]. In the scatter plots, each dot represents an electrode, and x and y axes indicate pRF center and y-coordinate on the cartesian grid of these electrodes, respectively. Colormap reflects the pRF center, as well as the tuning fingers.* ***a. Somatotopic maps in somatosensory cortex.*** *Electrodes in the the postcentral and precentral gyri are shown in the left and right plots, respectively. A regression analysis is performed to explore any positive relation between pRF center and y-coordinate of the electrodes.* ***b. Somatotopic maps in Precentral Clusters.*** *Electrodes in the precentral gyrus are divided into 2 clusters, and regression analysis is performed in each cluster separately.*

Significance: A previous fMRI study [1] from our lab found somatotopy in sensorimotor cortex using pRF method. Using direct brain recordings, our results also support these findings, and that is an important step towards a more reliable invasive BCI applications with finer capabilities.

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PIEEG: Performance Evaluation of a Motor Imagery Based BCI On a Low-cost, Raspberry Pi 4

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Introduction: Brain-computer interfaces (BCIs) offer a new way to interact with the world for children living with complex needs, but currently require expensive hardware and burdensome software to be used outside of the laboratory [1]. Due to the ongoing global chip shortage and the attempt to find suitable software for signal processing, researchers are seeking to find alternative low-cost BCI devices. Recent research has enabled a low-cost Raspberry Pi 4 (RPi4) to be BCI compatible for measuring and processing of EEG signals [2]. Understanding the behavior of RPi4 while it operates standard BCI procedures such as training classifier models is key to advancing practical applications. This work aims to do so while evaluating performance against traditional desktop and laptop computers to evaluate its potential for implementation beyond the lab setting.

Material, Methods and Results: We employed the BCI competition IV Dataset 2a [3] to evaluate four motor imagery tasks across 22 EEG channels performed by adult participants (n=9). Raw data were band-pass filtered between 7-35 Hz, lower and upper transition bandwidth were selected to be 2.0 Hz and 8.8 Hz respectively. Epochs of 3s were extracted from the dataset into 288 events of four classes (left-hand, right-hand, foot and tongue). Filter length of 413 samples (1.652 sec) was selected and 288 events loaded.

Feature extraction using wavelets and common spatial patterns was applied. Twelve machine learning models were then trained on RPi4, desktop (AMD Ryzen 7 5800X 8-core, 16GB), and laptop (Intel Core i7, 16GB, for Win OS & Mac OS) platforms. The trained models were: Linear discriminant analysis (LDA), K-nearest neighbors (KNN), Support vector machine (SVM), Random forest (RF), Logistic regression (LR), Naïve bayes (NB), Decision tree (DT), Ensemble bagging (EB), Ensemble boosting (EB), Ensemble stacking (ES), Riemannian geometry (RG) and Artificial neural network (ANN). The performance evaluation using the accuracy metric is shown in Fig.1a. Total execution time (tottime) spent in the given function is also shown in Fig.1b.

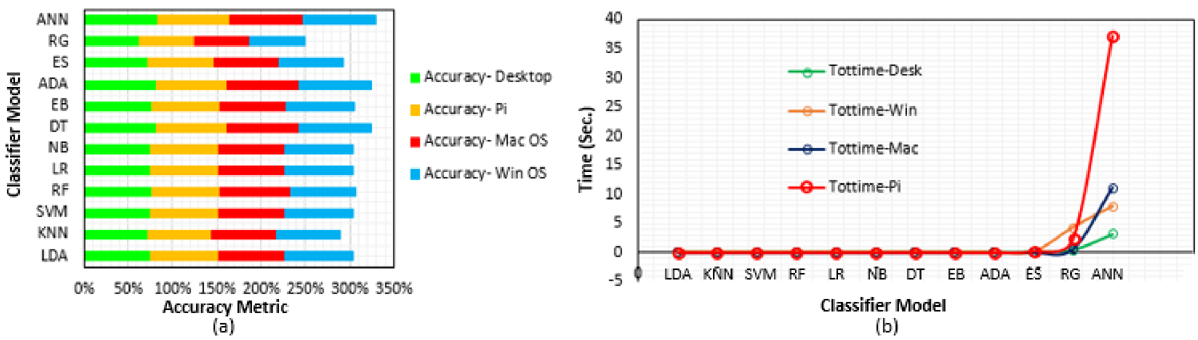

Figure 1. (a) Performance Evaluation on Pi, Laptop (Win & Mac OS) and Desktop (b) Total execution time of the Classifier Model profiling

Discussion: The present study demonstrates that RPi4 is a potentially viable device for low-cost BCI systems, but high-resource demanding classifiers such as ANN may need to be considered carefully in their implementation. The accuracy metric of ANN model achieved the best performance of 83% across all devices making 332% in total, followed by ADA and DT having 81% each, totaling 324% respectively. The total execution time for ANN is higher than the others, however RPi4 took more time to finish its task (which can further be investigated).

***Significance*:** Understanding the RPi4 profile while operating standard BCI procedures is important for the design of a low-cost high performance BCI control for real world applications to enable persons with severe disability.

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Decoding primary color responses in EEG signals with deep learning in the source space

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Introduction: The brain's response to visual stimuli of different colors might be used in a brain-computer interface (BCI) paradigm. Allowing the user to control certain elements in its environment by looking at corresponding signs of different colors could serve as an intuitive interface. This paper presents work on the development of a classifier for red, green, and blue (RGB) visual evoked potentials (VEPs) in recordings performed with electroencephalography (EEG).

Material, Methods and Results: The classifiers developed in this work were trained and tested on a dataset of primary colors (RGB) visual stimulation. The dataset contains 60-channel EEG recordings from 31 subjects. The RGB colors were displayed on a screen in front of the subjects for intervals of 1.3 seconds, in random order with 140 repetitions for each color. Three convolutional neural networks (CNNs) were explored for this classification task: A graph CNN (GCNN) [1], EEGnet [2], and deep convNet [3]. Intra-subject classifiers were developed for all 31 subjects. EEGnet and DeepCNN were trained in both electrode and source space. The best classifier, deep convNet using all electrodes, yielded an average accuracy of 77%. A previous study developing classifiers for the same dataset, using conventional machine learning, reported an average accuracy of 74.43% for a subset of subjects [4]. In this study, the same subset achieved an average accuracy of 84%. The best classifier was found using the deep ConvNet [3].

Discussion: The results indicate that it is possible to distinguish between the primary color responses. The hyperparameters of the three networks employed in this work have been left unchanged (except for some modifications necessary for integration). Considering this, it is reasonable to assume that some tuning of these hyperparameters could yield better results. The classifiers were expected to perform better in source space than electrode space, however, this was in general not the case. This unexpected result could be attributed to the fact that all three neural networks were originally developed for use in electrode space.

Significance: The results of this work demonstrate that it is possible to classify between primary color responses in EEG recordings. The results also show that deep learning methods can be suitable alternatives to traditional machine learning for decoding primary color responses.

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Inner Speech Decoding from EEG and MEG

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Introduction: Despite the prevalence of inner speech in everyday life, research on this has been limited, particularly when it comes to non-invasive methods [1]. Our study aims to fill this gap by using EEG and MEG to collect data from three different inner speech paradigms, and by conducting an initial decoding analysis. Such research has the potential to pave the way for word-level communication through brain-computer interfaces [2].

Material, Methods and Results: We conducted a study to examine the differences between silent reading, repetitive inner speech, and generative inner speech using five patient-relevant words (*help*, *hungry*, *tired*, *pain*, *thirsty*) in healthy participants. Our experiment consisted of two versions. Before and after each session, 5 minutes of resting state data were collected. For all sessions, we also collected ECG, EOG, EMG (on the jaw), and eye-tracking data.

In version one of the experiment, participants silently read words on a screen (one at a time), followed by a visual fixation-cross cue to repeat the word in their minds. In some trials, they were next prompted to imagine speaking a different word from the set of five (the generative inner speech task). All visual stimuli appeared for 0.8-1.0 seconds and are followed by a blank screen lasting 0.8-1.0 seconds. We collected combined MEG (Elekta Neuromag 306-channel) and EEG (Easycap 64-channel) data from 3 male participants, with 6, 2, and 2 sessions per participant, respectively. The resulting sessions consist of around 325 reading, 325 repetitive inner speech, and 250 generative inner speech trials, divided nearly equally between the 5 words (word selection was randomised). In version two of the experiment, instead of having a single cue, four consecutive crosses were shown, spaced at 1-second intervals so that participants repeated the word 4 times. We collected 1 session of combined MEG and EEG data from a male participant, 1 MEG and 1 separate EEG session from another male participant, and 1 MEG and 10 separate EEG sessions for a third male participant. Each of these sessions contains around 173 reading, 692 repetitive inner speech, and 640 generative inner speech trials.

For preprocessing, maxfiltered MEG data was bandpass filtered between 0.1-40Hz. It was further preprocessed using bad channel and segment detection, and artefact rejection with a 64-component ICA. Although several methods were tried, no significant decoding was obtained on the MEG inner speech data. On the reading trials of version one of the experiment, we trained a 2-layer linear neural network using the entire 1-second epoch with 20-fold cross-validation. For the participant with six sessions, 30% validation accuracy was obtained, with 44% for the other participants. The chance level is 20%. Using a sliding-window LDA model the peak accuracy was observed between 300 and 400ms post-stimulus.

Having analysed the MEG data, we next investigated the generative inner speech data from the 10 EEG sessions. EEG preprocessing consisted of a 1-40Hz bandpass filter, bad channel and bad segment detection. LDA models were trained on each session using the covariance over the 1-second epoch with 5-fold cross-validation. We found above-chance validation accuracy in only 3 sessions, with an average of 25%. Next, we trained a single LDA model across these 3 sessions, achieving 33% validation accuracy, with the following modifications; 4-second epochs of the four consecutive cues were used, mean session-level evoked response was subtracted from each trial, and mean session-level covariance was also subtracted from each trial.

Discussion: We explored the potential of decoding inner speech from a new MEG and EEG dataset through three paradigms across a few participants, but with a large number of trials. Our initial findings suggest that decoding word-level inner speech is challenging, and more effective methods are needed for non-invasive data.

Significance: Our study has the potential to provide a useful and more direct platform for building decoding models for BCI applications, due to the high number of trials. Having multiple sessions also allows for testing across-session performance. The use of three different paradigms can lead to a deeper understanding of the neuroscience of inner speech. However, we highlight the difficulty of decoding inner speech.

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Exploring wearable High Density Diffuse Optical Tomography (HD DOT) as a real-time BCI

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Introduction:

HD DOT is an advanced implementation of fNIRS (functional Near Infrared Spectroscopy) offering the promise of a wearable, inexpensive and non-invasive BCI. Current fNIRS BCI implementations are still prone to slow information transfer and high error rates[1]. This project proposes using a new generation of wearable HD DOT technology[2] to overcome these drawbacks. High Density data allows us to reconstruct 3D images of hemodynamic activity using DOT[2]. We aim to implement the first real-time HD DOT BCI and explore novel deep learning classification methods using physiologically interpretable images as inputs. Neural networks will be more robust in classifying these images than raw data streams - spatial and temporal HD DOT images promise enhanced classification accuracy.

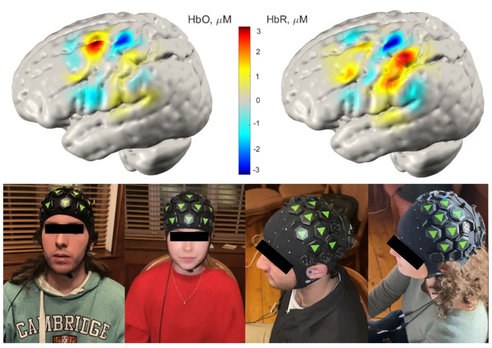

Figure 1: HD DOT images showing ***changes*** *in molar concentrations of oxygenated (HbO) and deoxygenated (HbR) hemoglobin during a motor task*

Materials, Methods and Results:

The LUMO[Gowerlabs, UK] is the state-of-the-art device used in this experiment, which offers a 100 fold improvement in cortical sensitivity compared to traditional fNIRS devices as used in previous BCI studies[2]. Currently, 13 participants have performed Motor Execution (ME), Motor Imagery (MI) and Mental Arithmetic (MA) tasks for our study. We used an interleaved experimental structure to obtain 660 unique activation blocks. Preliminary data analysis shows higher signal to noise ratio for MA tasks due to lower hair coverage over the prefrontal cortex. Using a 0.5Hz low-pass filter, we remove unwanted physiological noise (e.g. ∼1Hz heartbeat) and data with motion artefacts or low coupling efficiency has been separated. Offline regression using Linear Discriminant Analysis is being implemented with the preprocessed data to examine performance of the HD DOT BCI. We are analysing the HD data in a down-sampled and optimised fNIRS configuration to allow direct comparison with classical NIRS BCI implementations. HD DOT will give immediate improvements in classification accuracy - most classical studies arbitrarily place source-detectors in the appropriate region, whereas the high-density configuration allows us to choose the most responsive channels from more source-detector combinations. Choice classification mechanisms are being implemented to ensure smooth transition of the classifiers to real-time.

Discussion:

HD DOT images of the subjects have comparable resolution to fMRI[2] whilst allowing increased subject mobility - Figure 1 demonstrates the noticeable increase in concentration of oxygenated hemoglobin in the motor cortex during a motor task. Using real-time reconstruction of these images, deep learning classification methods are being implemented. This pioneers a completely novel classification mechanism for fNIRS BCIs.

Significance:

With the exponential growth in the BCI sector, a variety of different neuroimaging techniques are being explored. Unreliable and slow classification has rendered fNIRS not being as appealing to pursue commercially. HD DOT changes this, promising a higher performance, wearable, inexpensive and non-invasive alternative to the invasive BCI methods being explored. This research is foundational as no formal investigation into a real-time HD DOT BCI has been conducted - it would establish this novel neuroimaging technique as a competitive and convenient BCI allowing for wider funding and research.

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Distinct patterns of whole-body representation in human motor cortex and posterior parietal cortex

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Introduction: Understanding how different parts of the brain contribute to motor control is fundamental to both neuroscience and building effective brain-machine interfaces (BMIs). Traditionally, specific cortical locations within the motor cortex (MC) and posterior parietal cortex (PPC) have been linked to specific effectors [1,2]. However, recent work has found multiple effectors represented in small patches of MC and PPC [3,4]. How do we reconcile these conflicting results?

Materials, Methods, and Results: To address this question we recorded from single neurons in human PPC and MC (hand knob) as a subject attempted movements distributed from head to foot (left and right side of the body). Our results show that both MC and PPC code for effectors across the body, but with clearly distinct coding schemes. In MC, population-level tuning strength for the wrist and thumb was significantly stronger than other effectors. At the single neuron level, nearly all neurons were best activated by either the contralateral wrist or thumb and more weakly engaged by other effectors, most often the ipsilateral wrist and thumb. During simultaneous movements, neurons tracked the contralateral wrist and thumb, with little to no representation of the other effector. PPC represents the whole body as well, however, unlike in MC, there is similar tuning strength across effectors. At the single neuron level, roughly equal numbers of neurons were best activated by each tested effector, with a more random distribution of which other effectors were also encoded. Finally, in PPC simultaneous movements preserve the representation of both effectors.

Discussion and Significance: Choosing neural populations with appropriate functional properties is fundamental to both building an effective BMI and understanding its limitations. Our results provide information about the differences in functional properties of common target brain regions for motor BMIs. In MC, a strong representation of the contralateral hand supports choosing the implantation location based on the desired effector of control. While in PPC, equal representation across effectors supports a BMI that can be flexibly controlled by multiple effectors across the body.

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Decoding speech and internal speech on the single unit level from the supramarginal gyrus in a tetraplegic human

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Introduction: Speech is a natural and intuitive way for humans to express their thoughts and desires. Neurological diseases like amyotrophic lateral sclerosis (ALS) and cerebral brain lesions can lead to the loss of this ability, leaving patients without any means of communication. Brain-Machine-Interfaces (BMIs) offer a promising technological path to restoring communication by recording neural activity related to speech. While important advances in overt, attempted, and mimed speech decoding have been made, results in internal speech decoding are sparse, and have yet to achieve high functionality in real-time. We hypothesized internal speech would modulate single unit activity in SMG, due to its involvement in vocalized speech and other language processes.

Material, Methods and Results: In this work, a C5 - C6 tetraplegic patient implanted with Utah arrays in the supramarginal gyrus (SMG) performed an internal and vocalized speech task. In an offline task, trials were composed of six phases, beginning with a brief inter-trial interval, followed by an auditory or written cue to one of eight words (6 words, 2 pseudowords). Then, after a delay period, the subject was instructed to internally say the word, and after a second delay, to vocalize the word. We found single units tuned to words during cue, imagined and vocalized speech phases. Decoding accuracies averaged 55% for internal speech, and 74% for vocalized speech. An online task strictly using data recorded during internal speech was implemented. Online internal speech decoding accuracies increased with number of trials used to train the model and reached up to 91% accuracy (chance level ~ 12.5%). Shared representations between imagined and vocalized speech were demonstrated through overlapping tuned units and cross-classification analysis. Evidence for both phonetic and semantic representation were found by decoding words with identical semantic meanings and homonyms.

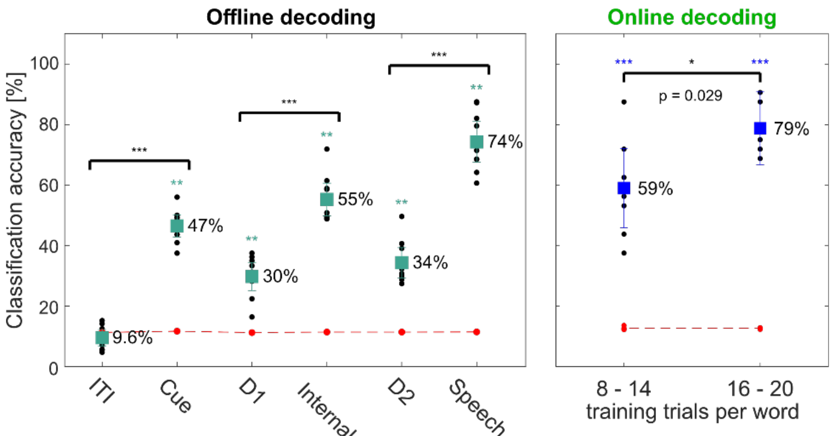

*Figure 1 Offline decoding accuracies: Leave-one out classification was performed on 10 individual session days (black dots). PCA was performed on the training data keeping 95% of the explained variance, a LDA model was constructed, and classification accuracies were plotted with 95% c.i, over the session means. Significance of classification accuracies was evaluated by comparing results to a shuffled distribution (averaged shuffle results = red dots, * = p < 0.05, ** = p < 0.01). Classification accuracies during action phases (Cue, Internal, Speech) following rest phases (ITI, D1, D2) were significantly higher (t-test: ***p < 0.001). Online decoding: Classification accuracies for internal speech were evaluated in a closed-loop internal speech BMI application, demonstrating significantly better decoding accuracies when increasing the number of training trials to construct the decoding model.*

Discussion and Significance: Current speech BMIs rely on the patient’s ability to produce sounds or movements of the mouth, which is not feasible for those affected by complete paralysis. Here, we show robust internal speech modulation within an area of the SMG, located in the posterior parietal cortex. The work provides proof-of-concept that internal speech BMIs can be built using multielectrode arrays implanted in a single brain area, and that findings could translate to the locked - in population.

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Continuous speech synthesis and articulatory kinematics decoding from intracortical neural activity

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Introduction: Brain-computer interfaces (BCIs) have the potential to restore speech in individuals who have lost the ability to speak due to ALS, stroke, or brain injury [1,2]. Intracortical BCIs have shown promise for high accuracy communication through attempted handwriting [3] and point-and-click typing [4], but these communication speeds are still slower than natural speech. Intelligible speech synthesis from a BCI has not yet been demonstrated. Here, we present ongoing progress in developing a neural decoder for speech synthesis using intracortical signals.

Material, Methods and Results: Neural activity was recorded from BrainGate2 clinical trial participant 'T5' (65 year-old male who has tetraplegia and intact speech) by implanting two Utah microelectrode arrays in dorsal (hand) motor cortex (originally for hand BCI studies) with a total of 192 electrodes (Fig 1a). We recorded neural activity and speech audio from 100 open-loop BCI trials (87 mins of speech) while T5 read out loud long passages.

We developed two multi-layered recurrent neural network decoders to (1) synthesize speech continuously and (2) decode articulatory kinematics from intracortical activity. To synthesize speech, we trained the decoder to estimate low-dimensional spectral and pitch features of speech from the corresponding spike band power of intracortical activity every 10 ms. We used the LPCNet vocoder to reconstruct audible speech from these speech features [5]. For estimating articulatory kinematics, we first used an acoustic-to-articulatory inversion model [6] to estimate kinematics trajectories of 18 articulator parameters during speech and then trained a separate RNN decoder to predict these kinematics from neural activity.

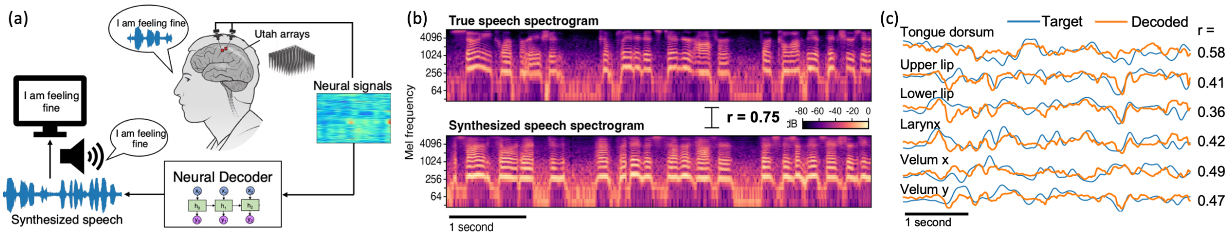

Figure 1. *(a) Speech BCI framework. (b) Speech synthesis from dorsal motor cortex. (c) Kinematics decoding for 6 example articulators.*

Offline speech synthesis from dorsal motor cortex activity yielded correlations of r = 0.75 ± 0.02 between the true speech and synthesized speech in 40 Mel spectrum bands (Fig 1b). We obtained a correlation of r = 0.42 ± 0.02 between the 18 target (estimated from audio) and decoded articulatory kinematics degrees-of-freedom (Fig 1c).

Discussion: Our neural decoder was able to synthesize speech offline with state-of-the-art accuracy. However, the reconstructed speech was not reliably intelligible, presumably due to low SNR for speech in the hand motor cortex. We view this work as a step towards developing intracortical speech BCIs recording from canonical speech brain areas, which may prove beneficial due to its potentially high SNR. We explored how a population of single neurons can predict articulatory kinematics, which could also be used for synthesizing speech using a vocal tract simulator.

Significance: We present a novel decoder framework towards developing closed loop intracortical speech BCIs for enabling high-speed natural and emotive communication. Future work will adapt the decoder to synthesize speech for people who cannot speak by generating synthetic voice data aligned to their neural activity for training. Our approach is language-agnostic and does not require a restricted vocabulary, facilitating general-purpose communication and multilanguage adaptation.

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Early safety data for retrieval of a stent-based endovascular neural recording array

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Introduction: Safe retrieval of implanted devices is critical when surgical/device complications occur, or when designed for non-permanant use. We have previously reported the ability of our endovascular brain-computer-interface (BCI), the Stentrode™, to access the brain via blood vessels and acquire brain signals endovascularly from the primary motor cortex [1]. Here we investigated retrieval of the Stentrode from within a dural sinus of sheep after an implantation period of seven days to explore feasibility of device retrievability and its potential to be used as a temporarily implanted neurodiagnostic tool.

Material Methods and Results: Corriedale ewes (2 adults, 18&24 months, 45&60 kg, respectively) were used, since their dural sinuses are comparable in size to those of humans [1]. We implanted a Stentrode (40mm long self-expanding closed-cell nitinol stent shape-set to 10mm diameter) in the left transverse sinus. The proximal connector was secured transcutaneously for data acquisition. A ring electrode, placed into a subcutaneous pocket (~5cm wide) between the two scapulae, was used as the reference during unipolar brain signal acquisition. To assess the quality of the Stentrode-acquired brain signals, we recorded, steady-state visually evoked potentials (SSVEP) (g.Tec system, 0-100Hz bandpass, 50Hz notch) in response to a visual stimuli flickering at 3&6Hz. The Stentrode was retrived 7 days after deployment. The animal was monitored and allowed to recover for 30 days. Post euthanisation, the implanted and control dural sinuses were sectioned for histological processing and stained (H&E, Masson's trichrome, and Voerhoff-Giesen). Histological assessment was performed according to a predefined grading scheme (wall injury, inflammation, fibrin, haemorrhage, necrosis score, & endothelial cell loss etc.). For both animals, high quality SSVEP neural signals were acquired immediately after implantation and the retrieval procedure 7 days post-implantation was safe for the animal's general health and its dural sinuses.

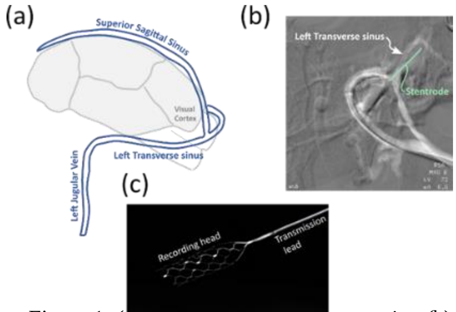

Figure 1: (a) Transverse sinus representation (b) X-ray image of the catheter assembly in the transverse sinus (c) Stentrode components.

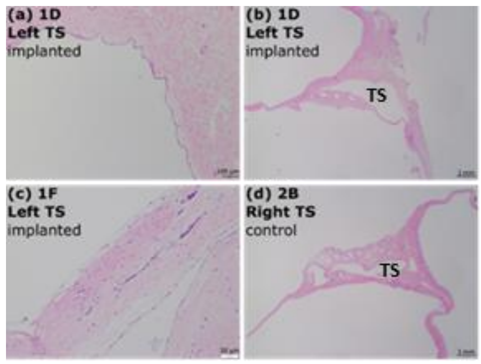

Figure 2: Histopathology of left TS (implanted) post-retrieval was similar to that of the control tissue (right TS). TS-transverse sinus, JV-jugular vein. (a) left TS with no histological lesions. (b) circumferential images of left TS with surrounding dura. (c) left TS, minor stromal inflammation, with scattered lymphocytes surrounding small vessels in the dural stroma. (d) circumferential images of the right (control) TS with surrounding dura.

Discussion: The device can record high quality signals shortly after implantation. The demonstrated feasibility of retreiving an endovascular BCI 7 days post-implantation supports further development of the Stentrode for application as a temporary recording device. A limitation of the study is that neointimal growth around implanted stent-like devices across weeks/months results in endothelialization. Complete endothelialization (>>7 days) may limit the retrievability of the Stentrode, a question that will be the focus of future work.

Significance: Retrieval of a stent-based endovascular neural recording array following 7 days of implantation can be performed with minimal to no observed effects on animals' general health and dural sinuses.

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Ultra-high-density electrocorticography recordings of the human sensorimotor cortex

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Introduction: The combination of high spatial and temporal resolution with limited invasiveness makes electrocorticography (ECoG) an important method in the study of neural implants. To optimize ECoG-based brain-computer interface (BCI) control while minimizing implantation risk, we aim to determine the optimal balance in cortical coverage versus electrode density. To do so, it is necessary to record from multiple neuronal ensembles simultaneously in great detail. This is made possible by the ultra-high-density (UHD) grids (0.9 mm pitch) produced by Cortec Neuro. To assess the advantages of UHD ECoG, we compared its signal quality to conventional high-density (HD) ECoG (3 mm pitch).

Material & Methods: We recorded from the human sensorimotor cortex during sleeping (n=2) and awake (n = 4) brain surgeries, for 5-15 minutes. Data was recorded with Cortec UHD grids (see Fig. 1), in most cases (n = 5) combined with simultaneous HD recordings (PMT or AdTech). During awake surgeries, the participants performed speech or hand movement tasks**.**

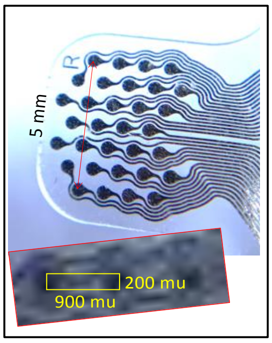

***Figure 1**. Dimensions of the Cortec ultra-high-density grid.*

Results: Visual inspection of the raw signals and power spectra shows that about 60% of the UHD electrodes appeared noisy compared to other electrodes in the same grid. We observed no significant difference between the power spectra of the UHD and HD grids (mean and standard deviation of the ten best channels). When computing the correlation of the mean high-frequency band (HFB) power signals (65-95Hz) between non-overlapping windows of 10s, we noted very high correlation between time windows, for both UHD and HD grids, suggesting stable signals over time. We quantified the extent to which each electrode recorded independent signals by computing the correlation of HFB power between electrode pairs for every 10s of data, and then averaging over time windows for all equidistant pairs [1]. Correlation values between UHD electrode pairs did not decrease with distance, while this clearly was the case for HD electrode pairs, either indicating the presence of correlated noise in the UHD recordings or recording of common signal due to e.g. volume conduction. Lastly, UHD electrodes also displayed highly spatially selective responses to task onset and offset, indicating clear distinction between adjacent electrodes.

Discussion: Overall, the signal quality of UHD and HD grids proves to be comparable. The results indicate that the electrodes of UHD grids record spatially distinct signals, despite the presence of shared features in the recordings.

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Exploring Recognition Methods for Asynchronous(un-cued) SSVEP-based BCI Speller System

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Introduction: Steady state visual evoked potential (SSVEP) is one of the prevalent paradigms to control massive class BCI speller, and there are two control modes in BCI systems such as asynchronous and synchronous systems [1]. There have been studies on the asynchronous system that operates according to the user's intent, and the different methods were used [2, 3, 4]. In this study, to explore in-depth efficacy of recognition method (detecting control state(CS) and non-control states(NS)) in 40-class SSVEP dataset, we tried to do comparative study for three recognition methods such as frequency power, canonical correlation analysis(CCA), and machine learning approach used in SSVEP studies.

Material, Methods and Results: 40-class SSVEP data from 40 subjects were collected using BioSemi ActiveTwo in the experiment(6 block×40 class, 2s of NS, 5s of CS). Eleven electrodes (among P1, P2, Pz, PO7, PO3, POz, PO4, PO8, O1, Oz, and O2) were used in this study. Three methods, the relative power of frequency and CCA coefficient, and support vector machine(SVM) using frequency power, were used as user intent detection methods. To determine a threshold and training SVM, a half of the trials are selected. Filter Bank-CCA having the advantage of identifying massive target numbers was applied to classification. The procedure of the asynchronous system is illustrated in Fig. 1.

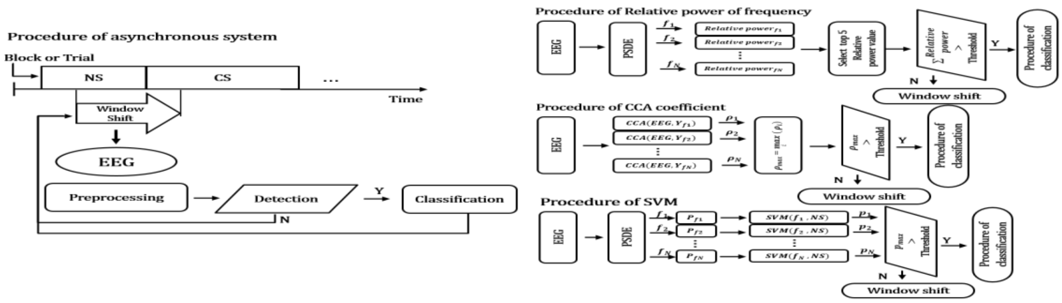

Figure1. *Procedure of asynchronous system and three methods for user intent detection.*

It was found that the detection accuracies of CS were CCA (97.62±2.08), frequency power (73.94±23.16) and SVM(33.67±19.21). Also, the detection accuracies of NS were CCA (76.50±21.78), frequency power(33.99±22.33) and SVM(80.39±14.04). Finally, we observed that the classification accuracies were CCA (75.55±10.96), frequency power(55.64 ± 17.29) and SVM(30.93±20.38).

Discussion: The performance of the CCA approach seems an efficient feature of user intent detection and classification. The SVM approach showed high performance in detecting NS, but low CS detection causes a decrease in classification accuracy.

Significance: We compared the user intent detection methods to apply a massive class (40-class) SSVEP speller system.

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Recording the Tactile P300 with the cEEGrid – Good, but not yet Perfect

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Introduction: Brain-Computer Interfaces (BCIs) enable their users to interact with the environment without requiring intact motor control. As such, they are particularly promising as an assistive tool for locked-in patients.

However, the conventional EEG cap setup, which is typically used in a BCI to record brain activity, is often considered too cumbersome for daily use outside the lab, which may contribute to the notable translational gap [1]. The cEEGrid, a novel and compact around-the-ear EEG [2], may offer a convenient solution for this issue. Several studies have already demonstrated that the cEEGrid reliably captured event-related potentials, including the P300, which are the basis of many BCI paradigms. This study aims to assess the cEEGrid's feasibility for the potential use in an already existing vibrotactile P300 BCI [3].

Material, Methods and Results: We recorded data from two cEEGrids and 12 passive scalp electrodes simultaneously using two BrainAmp amplifiers. Healthy participants (*N*=20) performed a tactile oddball task to elicit the P300. Target and Non-Target epochs were averaged separately for data extraction and plot generation. The P300 was offline classified via step-wise linear discriminant analysis. Both EEG systems captured a clearly visible P300 deflection (Fig. 1), but amplitudes were higher at the scalp positions, with up to 4.8 µV at Cz versus 2.3 µV at the cEEGrid's bipolar channel R2R7. Accuracies calculated from the scalp EEG were significantly higher as compared to the cEEGrid (*M*=85% vs. *M*=70%).

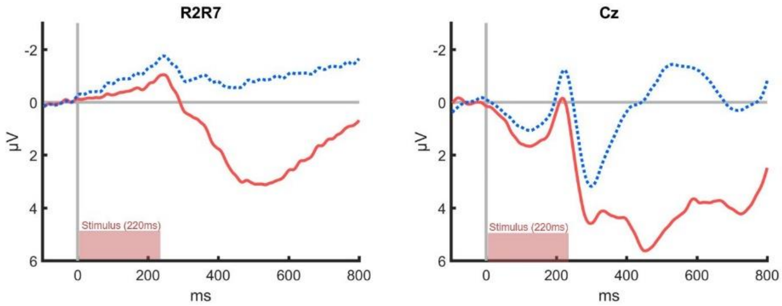

Figure 1: Target and non-target responses (grand-average). Highest amplitudes were observed on the cEEGrid's bipolar channel R2R7 and on position Cz at the cap-EEG.

Discussion: In line with several other studies, the highest cEEGrid ERP amplitude was found in the vertical bipolar channels [2]. Overall, ERP amplitudes found at the cEEGrid are typically smaller as compared to scalp positions, but signal strength (target/non-target discriminability) is not always negatively affected [2,4], resulting in classification accuracies on par with cap-EEG systems. In this study however, cEEGrid accuracies were smaller, although still significantly above chance levels [5]. Higher accuracies would be desirable to achieve a more efficient communication.

Significance: The present study adds to the growing list of list literature comparing the cEEGrid to conventional EEG-systems and provides first evidence that the cEEGrid records the tactile P300 in a quality sufficient for above-chance level classification. As such, the cEEGrid may help to establish BCIs among potential end-users.

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Riemannian vs. Linear P300 classification for a tactile Brain-Computer-Interface in an end-user single-case study

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Introduction: By creating an output directly derived from brain activity, Brain-Computer Interfaces (BCIs) allow people in a Locked-In-State (LIS) to interact with their environment. As classification optimization remains one of the main challenges of the domain, signal classification algorithms have been investigated regarding their suitability for application in the field of BCI. However, since most studies were performed with healthy participants, results may not be fully translatable to impaired potential end-users. Therefore, we aimed to investigate classifier performance on a dataset obtained from a potential end-user in the Locked-in State (LIS).

Material, Methods and Results: A patient in the LIS participated in a total of 17 sessions of a six-class tactile BCI training in his own home [2]. The obtained data were used to test four classifiers, in four calibration modes, to investigate their overall performance, their inter-session transferability and resilience against less training data. Shrinkage Linear Discriminant Analysis (shrinkLDA) and Riemannian Geometry Classifiers (RGCs, i.e., Minimum Distance to Mean (MDM) and MDM with a preceding Fisher Geodesic Discriminant Analysis (FGMDM)) were compared to a Stepwise Linear Discriminant Analysis (SWLDA), which was used during online classification.

In all sessions, the patient elicited a P300 with mean amplitudes of 1.9 µV at Cz (SD=1.7) in the window of interest 350-600ms after stimulus onset (see Fig. 1a). High variances in amplitudes and classification accuracies were observed between sessions and the different classification algorithms. No classifier was able to increase the accuracy significantly compared to the SWDLA used for online feedback in any calibration condition (see Fig. 1b for session-wise calibration (based on 180 target epochs)).

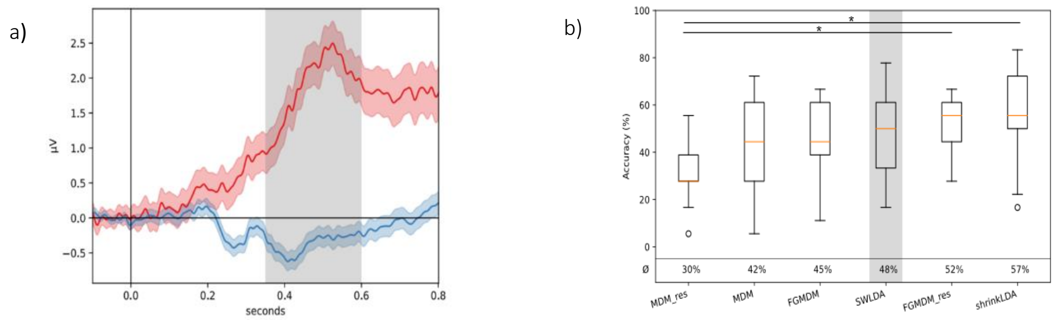

Fig. 1 a) Average P300 amplitude at Cz across all sessions. Red: Target, Blue: Non-Targets, Shaded areas indicate the 95% confidence interval, Grey: window of interest (350-600ms after stimulus onset). b) Boxplots of the accuracy for the implemented classifiers in one of the four calibration conditions (session-wise calibration (based on 180 target epochs)).

Discussion: Although, at least descriptively, the SWLDA appeared to be outperformed in certain conditions, no algorithm was able to perform consistently above the usability criterion level (≥ 70% accuracy) [3] across all sessions in any of the calibration modes, highlighting the urgent need for improvement in this domain. Further, classifier performances did not show clear consistencies in their ranking, and no single classifier always outperformed the others.

Significance*:* These results underline the importance of classification-algorithm selection and a considerable potential for improvement in the overall classification process. More emphasis should be put on research directed toward the classification of data obtained in actual use-cases, in non-laboratory conditions, particularly involving potential end-users with neurodegenerative disease.

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Effects of robotic-assistance in ERP modulation for upper-limb exoskeleton control

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Introduction: Event-related potential (ERP)-based brain-computer interfaces (BCI) are being widely explored in robotic neurorehabilitation because there is increasing evidence that involving the patient in their control loop improves brain plasticity and motor learning[1]. In particular, exoskeletons can provide different assistance levels (AL), which can be optimized with ERP-based BCI [2]. However, it is not clear if and how brain activity is affected by different AL, or whether it is possible to use this modulation as a metric for assessing the performance of the robot and of the patient. In this work we investigate ERP modulation during a standardized motor task with different AL provided by FLOAT -a novel upper limb exoskeleton developed by our group [3]- to better understand the relationship between brain activity and AL in robotic neurorehabilitation.

Material, Methods and Results: 10 healthy right-handed subjects performed a reaching task using a touch panel as shown in Figure 1.1. The task was repeated in four different conditions: free movement (FM) and assisted by FLOAT exoskeleton providing low, medium, and high AL, respectively. High-density EEG was recorded and used to calculate ERP, which was compared across different AL. We found significant difference in the ERP amplitude 150-450 ms after reaching the target, when comparing FM with medium and high AL, while no significant differences were observed when comparing with low AL.

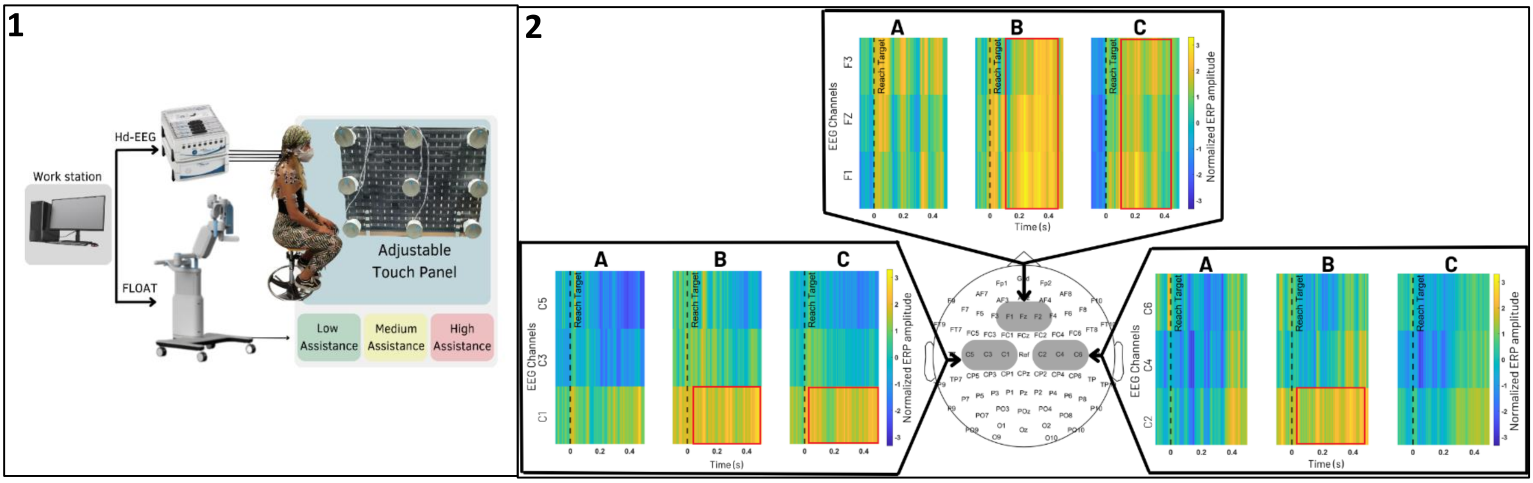

Figure 1. 1) Experimental setup.2) Differences in ERP amplitude between FM and A) Low AL, B)Medium AL, C) High AL, for the indicated EEG channels. Red squares indicate significant differences (p-value <0.05, computed with a cluster-based permutation using Montecarlo method).

Discussion & Significance: We found differences in ERP modulation in different brain areas - associated with movement planning and execution - when performing the reaching task assisted by the robot (Figure 1.2). The fact that there is no difference between low AL and free movement could indicate that the motor scheme is unchanged during this condition, and thus, the two conditions are perceived as similar. Understanding the effects of different AL on brain activity could have important implications for BCI design: It can provide new insights about neural mechanisms of human-robot interaction that could be used to improve human-in-the-loop optimization strategies for neurorehabilitation.

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Tackling Motor Imagery Based BCI Illiteracy through a Novel Augmented Reality Paradigm

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Introduction: Motor imagery (MI) - the mental rehearsal of movement without motor output - is widely used as a control strategy for Brain-Computer Interface (BCI) because it elicits similar neural responses as real movement, while it is low cost, non-invasive and safe [1]. However, 15-30% of MI-based BCIs users are 'BCI illiterates': they are not able to control the system [2]. To overcome this, we propose a paradigm combining MI with action observation (AO) -deliberate and structured movement observation- supported by augmented reality (AR), to explore its effects on motor-related brain responses that could potentially enhance MI-based BCI paradigms.

Material, Methods and Results: Twenty-five healthy participants performed a reaching task - either imagined (Motor Imagery-MI) or real (Movement Execution-ME) - with the right arm using a touch panel (Fig. 1A). The task was repeated with (REAL CONDITION) and without AR (AUGMENTED CONDITION) in a randomized order, the former showing a virtual right arm in order to provide an AO cue. We analyzed electrophysiological (EEG) signals by computing event-related desynchronization (ERD) in the alpha and beta band during movement execution/imagination, with a baseline of 500 ms before movement onset.

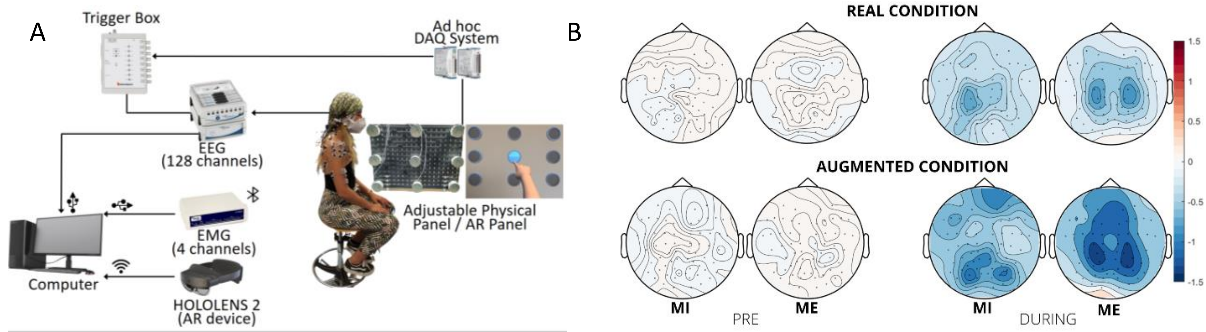

Figure 1. *a) Experimental setup. b) Topographical map showing ERD (dB) from Motor Imagery (MI) and Motor Execution (ME) before (PRE) and during (DURING) motor imagination/execution in physical and augmented condition.*

We found no significant difference between MI and ME groups in terms of ERD power (one-way ANOVA, $p<0.05$). Moreover, we observed that AR produced movement-related ERD power in specific brain areas (such as in parietal, frontal and central regions), comparable to pure motor execution brain activity (Fig 1B).

Discussion & significance: Our results support previous research suggesting that simultaneous usage of first-person perspective AO (through AR) and MI act in an additive manner over several brain areas [3]. Our main finding is that our novel MI paradigm elicits an ERD response that is comparable to movement execution, [4]. This suggests that the implementation of auxiliary tools/techniques like AR -that facilitates MI by enhancing sensory cues- could drastically improve MI-based BCI training and usability by eliciting stronger brain responses that can be more easily detected and classified by the BCI system. This strategy might boost the application of BCIs in neurorehabilitation and the interaction between human motor control and assistive technologies.

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Decoding articulatory trajectories during speech production from intracranial EEG

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Abstract

Introduction: Speech Brain-Computer Interfaces (BCIs) are a technology that can help restore the ability to communicate of people with neurological impairments, aiming at synthesizing speech from brain signals. Most studies have focused on directly decoding text or speech segments like phonemes or words. However, it is unclear if this is how the speech production process is represented in neural recordings. An interesting approach is to model the behavior of the vocal tract, which has been successfully decoded from several brain areas. The vocal tract is composed of different physiological structures called articulators (i.e., the jaw, velum, and lips). The combination of all articulators' position and movement define the sounds heard during speech production. Recent advances have made it possible to reconstruct speech from these articulators' time trajectories, making them a good candidate for the construction of speech BCIs. This study will investigate the possibility of decoding articulatory trajectories from minimally invasive electroencephalography.

Materials and Methods: With this work, we will systematically evaluate the decoding of articulatory trajectories from neural signals and, thus, the feasibility of constructing speech BCIs with articulatory trajectories as an intermediate representation. We plan to use the SingleWordProductionDutch (SWPD) dataset presented by Verwoert *et al.* [2] where 10 participants read out individual words while stereotactic electroencephalography (sEEG) and audio data was measured.

Results: We extract articulatory trajectories from the audio using the model presented by Gao *et al.* [1]. From the sEEG recordings, we extract the high-gamma power, which contains highly localized information about speech processes. Fig. 1 shows the location of the sEEG electrodes implanted in one of the subjects from the SWPD dataset, as well as the articulatory trajectories from one recording. We train a linear regression model to predict the articulatory trajectories directly from the neural data and evaluate the reconstruction through the correlation with the actual trajectory.

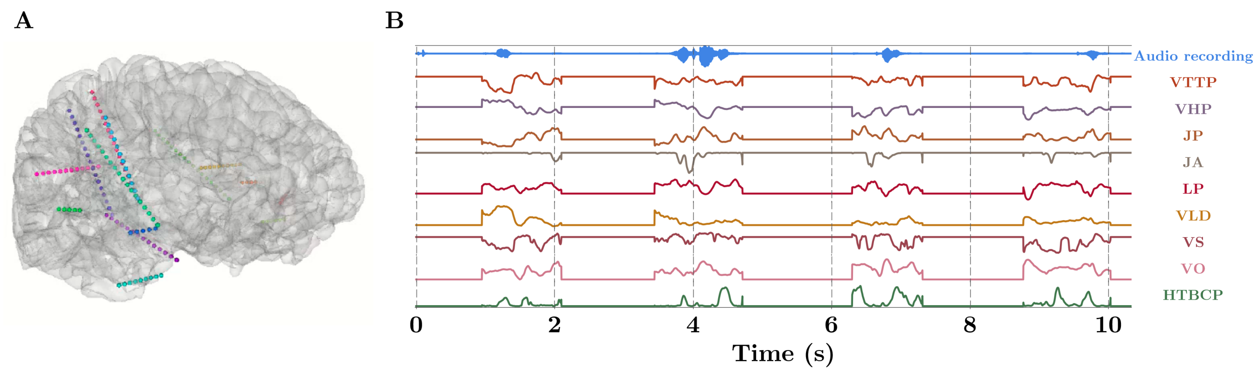

Figure 1: A Right lateral view of the electrode locations (subject 6, SWPD dataset). **B** Audio waveform and sample of the extracted articulatory trajectories for 10 seconds of data (subject 6, SWPD dataset). VTTP: Vertical tongue tip position, VHP: Vertical hyoid position, JP: Jaw position, JA: Jaw angle, LP: Lip protrusion, VLD: Vertical lip distance, VS: Velum shape, VO: Velum opening, HTBCP: Horizontal tongue body center position

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Brain-computer interface training fosters perceptual learning

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Introduction Perceptual learning improves our ability to make decisions amidst ambiguous sensory information by intense training [1]. Given the established evidence associating the amplitude of the error positivity (Pe) component of error-related potentials (ErrP) with conscious awareness [2], we conjecture that there is a casual relationship between the Pe amplitude and humans perceptual ability to detect visuo-motor errors (Fig. 1a). We predict that participants cannot improve their ability to perceive small errors by conventional perceptual learning training. For these small perceptual errors that subjects failed to learn to detect, we expect Pe amplitudes to remain small. Furthermore, we hypothesize that providing BCI feedback on the presence/absence of ErrP during perceptual training will enhance the Pe component, and thus augment perceptual abilities of participants in comparison to a conventional perceptual learning protocol without BCI feedback.

Material, Methods and Results Thirty-two healthy participants used a joystick to control a cursor from a start to an end location in a computer screen following a straight, continuous trajectory (Fig. 1a). An experimental session consisted of 10 training runs, each with 32 reaching trials. In each trial, the normal joystick-cursor mapping can be violated by applying a rotation magnitude. To control the levels of difficulty to perceive errors, we used four magnitudes of rotation: 3, 6, 9 and 12 degrees. Participants in the BCI and the control groups (16 each) completed perceptual training over 5 consecutive sessions, where they received feedback at the end of each trial. The control group pressed joystick buttons to indicate whether they perceived a rotation and received the correct answer. Feedback for the BCI group was the output of their BCI (detection of an ErrP) together with information about an eventual rotation. The results show that BCI intervention fostered perceptual learning at small rotation magnitudes of 3° and 6° (Fig. 1b). The BCI group also showed significantly enhanced Pe amplitudes at Cz across sessions, which mirrored the behavior improvement in perceptual abilities (Fig. 1c).

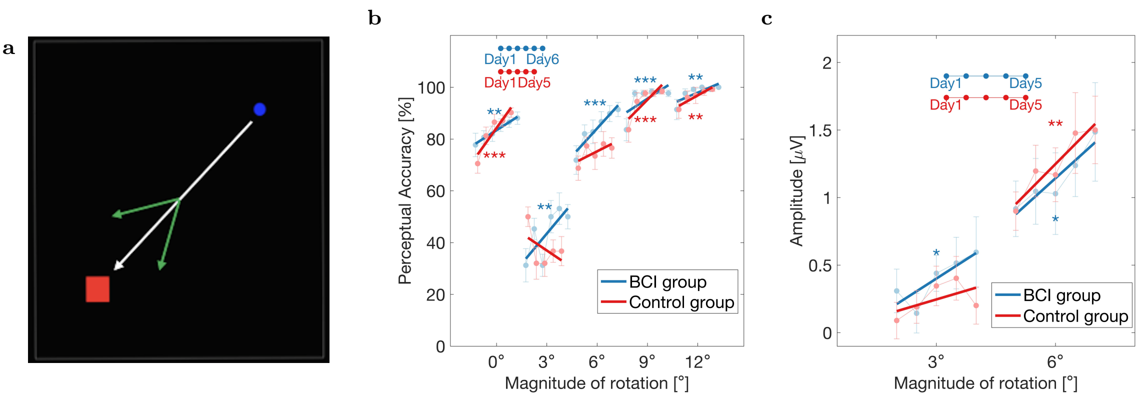

Figure 1: **a** *The cursor control task, the green arrows indicate directions where the cursor could be rotated.* **b** *The accuracy of subjects' perception to rotations (No rotation, 3°, 6°, 9°, 12°) over sessions.* **c** *The change in Pe amplitudes at Cz across sessions in 3° and 6°.* $*$: $p < 0.05$, $**$: $p < 0.01$ *and* $***$: $p < 0.001$

Discussion and Significance Our results revealed that humans' perceptual abilities to identify errors during cursor-reaching movements is closely related with ErrPs, and such cognitive brain function is, in part, governed by Pe amplitude of ErrPs. The proposed BCI-based approach can provide foundations for future non-pharmacological, non-invasive interventions for perceptual impairment in elderly and clinical populations, which avoids the adverse effects of pharmacological interventions and accelerates perceptual learning in comparison to time-consuming, conventional methods.

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A Case Study in BCI Skill Learning: Preliminary Results from a Longitudinal BCI-Power Mobility Study

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Introduction: Brain-computer interfaces (BCIs) are well-positioned to increase independence and participation for people with disabilities. BCIs have enabled children with quadriplegic cerebral palsy (QCP) to experience independent movement through access to power mobility devices (PMDs) [1]. However, both BCI and PMD control are skills that must be developed over time [2], [3]. BCi-Move, a multi-centre, longitudinal case study, was designed to investigate whether dedicated training can help children with QCP learn to use BCI to reach personal mobility goals. Learning of BCI-PMD skills can be characterized in many forms; one way is by identifying whether users can gradually produce more distinct and stable brain patterns, which could lead to more accurate BCI control [4].

Methods & Results: For BCi-Move, children with QCP (n=30 across 4 sites) will participate in a 12-week BCI-power mobility training program. Study recruitment and data collection are ongoing, but here we present results for the first participant. A cap-style Emotiv Flex headset with 14 saline-based electrodes was used for the hardware, and each training session started with 12 runs of motor imagery (MI) calibration. Results for 2 commands ("push" for forward, and "neutral" for no movement) are presented. To explore MI learning, 2 user skill metrics were quantified and compared with classification accuracy. These metrics are class distinctiveness, a measure of how distinct classes are from one another, and class stability, a measure of much variation there is in each class [4]. For signal processing, EEG signals (sampled at 128Hz) were filtered between 8-30Hz and epoched (2s segments). Covariance matrices were estimated for each epoch and used to calculate class distinctiveness and stability. The Riemannian minimum distance to the mean (RMDM) algorithm was used for classification. Class distinctiveness was observed to increase on average over the training sessions, stability of the 'push' class was observed to decrease, and no trend was observed for stability of the 'neutral' class. Significant variability was seen across sessions for all metrics. Classification accuracy was strongly positively correlated with class distinctiveness, and more weakly correlated with stability.

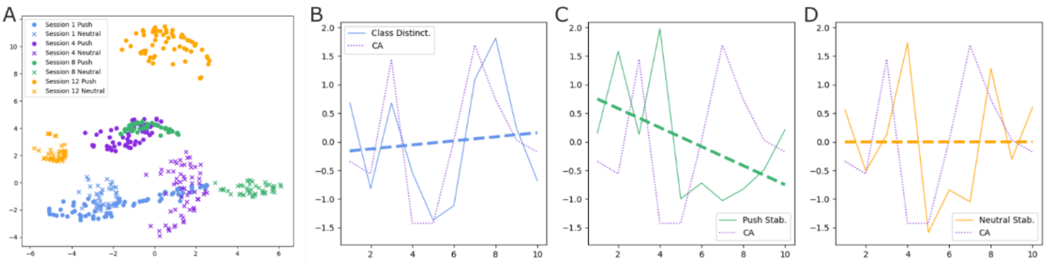

Figure 1: A) t-SNE visualization of the covariance matrices for each class (push = dots, neutral = x's) for 4 of the training sessions - session 1 (blue), 4 (purple), 8 (green) and 12 (orange). B)-D) Z-scores of class distinctiveness, push stability, neutral stability, respectively across all sessions. Metric trends are indicated with the bold hashed line. Z-scores of classification accuracy are also plotted in purple (dotted line) on each.

Discussion & Significance: Across the 12 training sessions, class distinctiveness increased on average, indicating the participant was gradually learning to produce more distinct brain patterns. However, the stability of each class did not appear to increase over time. Psychological factors, including mood, fatigue and motivation may have impacted learning on different sessions days, contributing to the observed variability. In addition, the participant was not provided with feedback based on these metrics during calibration; rather, visual feedback was based on classification accuracy. Incorporating user skill metrics as feedback during training could be more meaningful and help users produce more distinct and stable brain patterns, thus leading to increased learning and better BCI performance. Here we have demonstrated a preliminary exploration of BCI user skill learning across longitudinal BCI-PMD training for a child with QCP. A deeper understanding of how BCI skills are learned can help us design better BCI systems and support end-users in reliable, long-term use of BCI.

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EEG-based Decoding of Auditory Attention using a Deep Attention Network: Revealing neural commonalities of selective attention across individuals

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Introduction: Focusing on specific sound sources in cluttered environments is crucial for daily communication. However, this ability poses a great challenge for persons that are dependent on hearing aids, as the devices do not possess information about which speech sources are interesting to the user. To solve this problem, approaches from the field of auditory attention detection (AAD) are trying to develop cognitive models of auditory selective attention using electroencephalography (EEG). Here, subject-independence (SI) is useful for EEG-applications in AAD because it eliminates the need for pretraining on specific individuals, making the model more flexible and adaptable to a wider range of users. This allows the model to be applied to new persons without the need for additional data collection and training, making it more efficient for practical applications. Such models could expand our understanding of the cognitive processes involved in selective attention. Further, an integration into hearing aids in future applications would allow individuals with hearing impairments to regain a level of normalcy in their daily activities.

Materials, Methods and Results: This study aims to investigate subject-independent auditory attention decoding using EEG and Deep Neural Networks (DNN). The EEG data set in this work is publicly available and widely used in the AAD community [4.]. Participants were presented with two simultaneous but spatially separated speech stimuli, with the instruction to focus on one of the speech streams while their 64-channel EEG signals were recorded. The decoding task is a binary classification of the attended speaker in a given time window. To achieve this, the data was preprocessed and analyzed using a Deep Attention Network [1.], which is designed to be a lightweight and efficient architecture to process raw windows of EEG signals. The network uses spatial and temporal attention modules to extract EEG-channel interactions and temporal dynamics at different frequencies. The EEG-data was lightly processed by common-average referencing and filtering the signal between 1-32 Hz, followed by segmenting in 1 second non-overlapping windows for each of the 16 participants. The network was trained to classify the attention states of the participants based on the EEG data in a leave-one-subject-out cross-validation. The results show an accuracy of 72% (STD: 11%) over all 16 participants with all but 1 participant significantly outperforming the baseline of 50%. Excluding the 6 subjects below 70% as a threshold of practical performance, the remaining 10 subjects average an 80% accuracy (STD: 6%). The extraction of the spatial maps of the network allows an insight into the importance of each channel for the classification model. The averaged electrode weights for participants reveal strongly localized activations in the prefrontal and temporal lobes (AF7, AFz, AF8, T7, T8) with an average standard deviation of 5% of the mean between the participants, for all channels.

Discussion: The attention network significantly outperforms former DNN approaches for subject-independent auditory attention ($p < .01$) [3.] by an absolute of 7% (accounting for all participants) and has a lower variance between participants. While the spatial weights only reflect a part of the DNN-models, they imply a shared neural processing between the individuals in the prefrontal and temporal lobes. These areas are known to play a crucial role in speech tracking during selective listening [2.], and are likewise used by the neural network to discriminate between the different speech streams.

Significance: The attention network reaches state-of-the-art performance for subject-independent auditory attention decoding with lower variability and less than 4000 parameters while allowing an intuitive visualization and interpretation of modules of the model. The ability to decode auditory attention in a subject-independent manner is crucial for the development of cognitive models that can be applied to a wide range of individuals, including those with hearing impairments.

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Scanning electron microscopy data of 980 intracortical microelectrodes, implanted in three humans for recording and stimulation of cortical networks

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Introduction: Long-term stability of the microelectrode arrays is a fundamental requirement for the viability of brain-machine interfaces (BMIs) as therapeutic devices. These BMI devices hold significant promise to accomplish a variety of clinical outcomes, by capturing neural activity and using signal processing to decode an extraordinary amount of detailed information: motor planning and intent, high-level cognitive goals, speech and language, and dysregulated neural activity. Furthermore, they can inject information into cortical networks via electrical stimulation, creating novel sensory percepts, visual stimuli and stabilizing dysregulated neural networks.

Material, Methods and Results: Using scanning electron microscopy (SEM), we performed physical characterization of changes in the electrode metallization and insulation after long-term implantation in the human cortex. We imaged 980 electrodes, across eleven arrays (NeuroPort, Blackrock Microsystems, Salt Lake City, UT): eight arrays with platinum (Pt) electrode tips and three with sputtered-iridium oxide (SIROF) tips. Ten of these arrays were implanted across three human participants with tetraplegia. Two participants were implanted in anterior intraparietal area (AIP) and Brodmann's area 5 (BA5) for a duration of 5 yrs, 5 months and 5 yrs, 10 months. Another participant was implanted in primary motor (M1) and sensory (S1 area 1) cortices, bilaterally, for 2 years, 7 months. Three different clinical sites performed the implant and explant surgeries (Caltech - UCLA/USC and Johns Hopkins).

We found the physical state of the electrodes significantly correlated with measured noise, signal-to-noise ratio (SNR) and impedance (as measured *in vivo* prior to explant). We also categorized degradation outcomes ("pockmarked" vs. "cracked") for stimulating and non-stimulating electrodes as a step in the process of evaluating mechanisms for these effects. Physical damage was significantly spatially auto-correlated, suggesting biological degradation. From our data, we hypothesize erosion of the silicon shank often precedes damage to the tip metal, accelerating damage to the electrode / tissue interface.

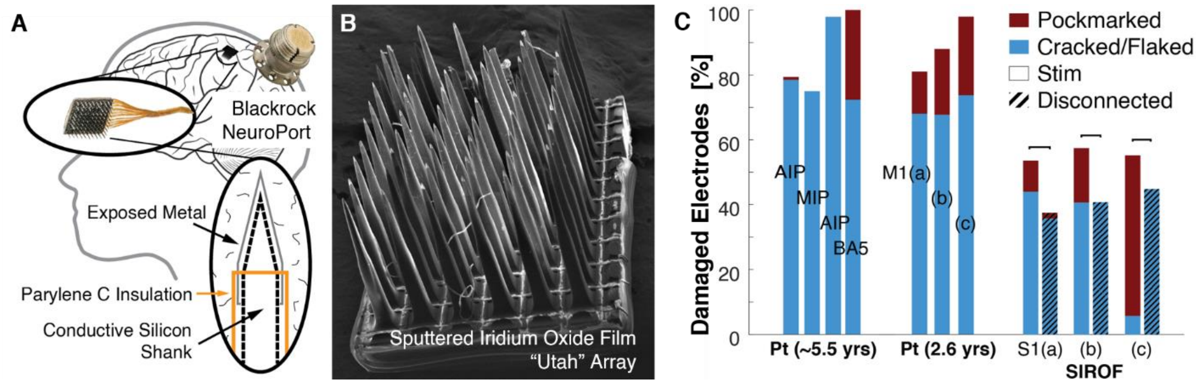

Figure 1. (A) Illustration of chronically implanted arrays and schematic of electrode design. (B) SEM image of a 6x10 "Utah" micro-electrode array after 2.6 years in-dwelling, tipped with iridium oxide electrodes. This 20-80kOhm impedance interface allows for recording and stimulation on each electrode. (C) Two unique tip degradation types were identified ("pockmarked" and "cracked"). The "pockmarked" degradation significantly occurred on stimulation electrodes while rarely occurred on non-stimulation electrodes.

Discussion and Significance: These findings link quantitative measurements, such as 1 kHz impedance, signal-to-noise ratio and RMS noise, to the physical condition of the microelectrodes and their capacity to record and stimulate. They provide researchers useful information and actionable insights for the day-to-day experimental process. These data are vitally important as multi-year clinical trials of BMIs are becoming more common and could lead to improved manufacturing or novel electrode designs to improve long-term performance of BMIs.

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A systematic review of invasive brain-computer interfaces in humans: current state-of-the-art and features associated with accuracy of an invasive BCI task

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Introduction: Brain-computer interfaces (BCI) may be broadly divided into invasive and non-invasive types. Invasive BCI is the current gold standard for providing neural signals with the highest temporal and spatial resolution. Advances in the last decade of invasive BCI has resulted in numerous cases being reported on various implanted devices used for decoding and restoring neurological function in humans[1,2]. We conducted a systematic review and individual patient data meta-analysis (IPDMA) summarising the existing international literature on invasive BCI to provide a road-map of the current state-of-the-art in invasive BCI technology as well as to identify features associated with accuracy of completing an invasive BCI task.

Methods and Results: We conducted a systematic review of Medline, EMBASE, and Cochrane databases until March 2022. We included articles reporting primary research on the use of invasive BCI in human patients for decoding or restoring neurological function. We excluded articles that used non-invasive BCI, articles reporting only signal analysis techniques, and articles in foreign languages. The study followed PRISMA guidelines and was registered on PROSPERO (CRD42022324796). 1128 titles and abstracts were reviewed by two independent researchers, and a total of 40 articles were included in the systematic review. Data was extracted using a standardised form, summarised using descriptive statistics, and IPDMA was conducted using multivariate linear regression models.

Invasive BCIs were implanted in patients for control of a digital interface or robot (n=23), identifying the neural correlates of a functional task (n=11), or for neuro-rehabilitation (n=6). Invasive electrodes utilised include implantable electrocorticographic arrays, microelectrode arrays, depth electrodes, and endovascular stentrodes. Data from a total of 94 individual patients across 32 articles performing a BCI task were pooled and the mean accuracy was 81.1 (standard deviation 16.1). The mean age was 33.3 (standard deviation 13.4), 37 (39.4%) patients were females, and 73 (77.7%) patients had epilepsy. Multivariate linear regression showed that female gender (β=7.34; 95% CI 0.05-14.63; p=0.048), as well as sensory and speech tasks (β=19.2; 95% CI 3.52-34.9; p=0.016) compared to motor tasks were associated with increased BCI task accuracy after controlling for confounders.

Discussion and Significance: This systematic review summarizes the progress and state-of-the-art in invasive BCI applications over the last two decades. Advances in invasive BCI technology have resulted in increased accuracy and performance of increasingly complex BCI tasks, including high-performance text and speech communication. Further technological advances in invasive sensors, device stability, and computational algorithms will continue to improve BCI performance in the future.

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Shared Brain Activity During the Creative Process and Dance Performance of LiveWire

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Introduction: LiveWire is an art-science performance that integrates research, training, and outreach at the nexus of the arts (music/dance) and neuroscience. The five sections of the musical score are inspired by neuroscience concepts, from the unconscious sub-routines that underlie our habits to the dynamism of thought: this is reflected in the choreography, which evolves from more constrained movements to structured improvisation. Shared brain activity from two dancers was acquired in real-time using mobile brain-body imaging (MoBI) technology and incorporated into the aesthetics of the performance through lighting and projections. This art-science project was designed to investigate intra- and inter-brain communication dynamics and networks during a series of rehearsals and public performances.

Material, Methods, and Results: Over the span of five months, two professional dancers were recorded simultaneously via 32 channel electroencephalography (EEG) at 1000Hz, motion sensors (128Hz), and video cameras (30fps). EEG data was denoised using a signal processing pipeline that included an adaptive scheme to remove eye movement artifacts [1], artifact subspace reconstruction (ASR) [2], and independent component analysis (ICA). Task related ICs were clustered using a k-means algorithm with a centroid number (k) computed by the Calinski-Harabasz algorithm [3]. Clusters were visualized in the MNI MRI template and analyzed to yield brain-to-brain communication networks between the dancers (See Fig. 1). Such networks indicate shared neural synchrony, estimated via bispectrum, following methods in [4] and functional connectivity, estimated via generalized partial directed coherence (gPDC) as in [5].

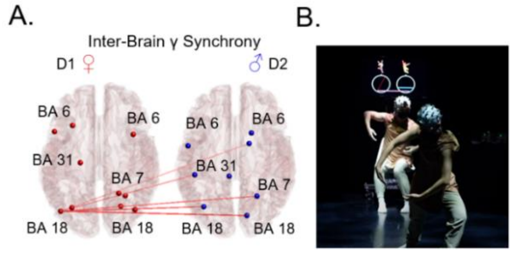

Figure 1. *Section three ('Internal Model of Reality') of the LiveWire performance at the Midtown Arts & Theater Center Houston (MATCH), held on 01/21/22. A) Five most significant average inter-brain neural synchrony connections across this section in the gamma frequency band showing synchrony between conscious and alert subjects mainly connecting in the occipital lobes. The brain on the left represents female dancer 1 (D1) and the right for male dancer 2 (D2), with both containing their respective dipole coordinates in shared Brodmann Areas (BA). B) A still frame of the dancers as they perform this section.*

Discussion: Our study demonstrates the use of MoBI technology to study the social brain in action in artistic contexts. Cluster analysis of ICs, neural synchrony, and functional connectivity of denoised EEG uncovered Brodmann areas related to movement planning and execution, visual processing, and proprioception and how their activations relate to each other within and across brains. Notably, when looking at bispectrum estimates in time across the performance, higher levels of neural synchrony were observed when the two dancers interacted with each other.

Significance: The integration of art, science, and MoBI technology in natural settings allow us to address questions of societal impact, e.g., neural dynamics of social interaction and the neural basis of creativity.

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Riemannian Transfer Learning for Pediatric Brain-Computer Interfaces (BCI)

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Introduction: Brain-computer interfaces (BCI) can provide a method for children with severe neurological disabilities to achieve their right to self-expression and life participation [1]. Pediatric users typically have less success in the calibration of BCI systems compared to adults because typical BCI calibration is not engaging for them. For this reason, children have much to gain from transfer learning methods which use previously collected source data to reduce or eliminate the required calibration. Riemannian geometry (RG) methods for transfer learning have been successful in adult populations [2, 3] but have not been examined in children. This work investigates the performance of existing RG transfer learning methods when applied to pediatric data.

Materials, Methods, and Results: Left/right hand motor imagery (MI) data was collected from 24 typically developing children (ages 6-16, median 10, 19 were female). The collected EEG data consisted of 18 intervals for each hand, each interval containing 6 epochs of 2s, totaling 320s. For each subject, “target data” describes that individual subject’s session data, while “source data” describes the cumulative data from all other subjects. Different methods for Riemannian transfer learning were tested with 5-80% of the target data to simulate shorter calibration durations. Direct (DCT), Recentering (RCT), and Riemannian Procrustes Analysis (RPA) methods were explored [3]. Calibration using only target data served as a control. All methods used the same Riemannian distance to mean (MDM) base classifier [4]. The trends shown in Fig. 1. indicate that RCT is an effective method for calibration durations from 0-100s (~30%), while RPA performs at or slightly above calibration in terms of accuracy for durations >200s (~60%).

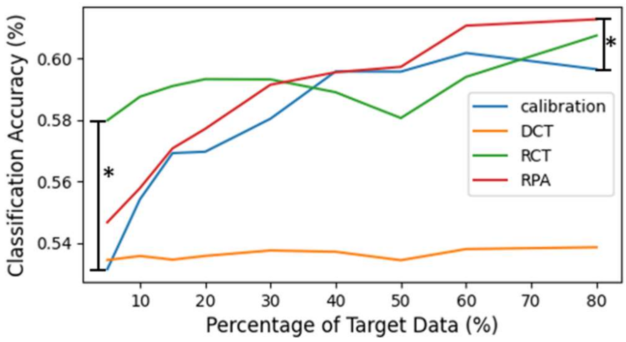

Figure 1. Mean classification accuracy with different amounts of target data. Calibration only uses target data. Direct (DCT) uses only source data. Recentering (RCT) and Riemannian Procrustes Analysis (RPA) use both source and target data. * - indicates $p < 0.05$ based on related t-test.

Discussion: This evidence suggests that Riemannian methods for transfer learning can offer better accuracy with both short (RCT) and long (RPA) calibration durations. This suggests transfer learning is a suitable choice for improving pediatric BCI when source data is available. The classification accuracy shown, although improved, is lower than commonly reported in adult studies. Further work should determine if transfer learning can help optimize pediatric BCI performance.

Significance: This work demonstrates that Riemannian transfer learning methods can improve accuracy and reduce the required calibration duration for pediatric users of motor imagery brain-computer interfaces.

Acknowledgments: We would like to thank the Alberta Children’s Hospital Foundation for funding this work.

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Detection of movement preparation-related slow cortical potentials using Riemannian geometry and template matching

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Introduction: Slow cortical potentials such as the Readiness Potential (RP) or the Contingent Negative Variation (CNV) precede self-paced or cued movements, respectively. Since these neural patterns are related to movement preparation, they can be exploited in several brain-computer interface (BCI) applications, such as robotic exoskeleton control or neurofeedback training. Nevertheless, reliable detection of such patterns is a challenging task. Here we present a novel technique for this purpose that might alleviate some of the shortcomings of previous attempts in the literature.

Material, Methods, and Results: We utilize Riemannian geometry and template matching for pattern detection from electroencephalography (EEG) data, while an adaptive re-centering step is incorporated to reduce non-stationarities between train and test datasets [1]. Each epoch is first concatenated with a previously obtained, subject-specific RP or CNV template. Then, covariance of the composite signal is computed, resulting in a matrix C_i that captures both the covariance structure of the data, as well as how it reflects the target template. Finally, C_i is re-centered so to standardize its distribution and thus reduce non-stationarities. Such covariance matrices then can be utilized in a re-biased Riemannian geometry classification framework [2]. To test our method, we recruited 12 young, healthy volunteers (4 females, age: 26.3±4.8 years) who performed a center-out reaching task on a touchscreen computer. The task was designed to evoke RP and CNV in a sequential manner (self-paced and cued movements, respectively), also incorporating baseline trials for both conditions. EEG was recorded at 512 Hz sampling rate from 9 cortical locations during task performance. Each subject completed 8 runs, resulting in a total of 120 trials for both RP and CNV (and equally for their baselines). Data was evaluated pseudo-online utilizing a leave-one-run-out cross validation scheme. We could detect RPs with a group average accuracy of 62.64±4.75%, while CNVs could be detected at 74.01±7.49%. CNV could be detected well above chance level for all subjects, while RP for all but one.

Discussion: The contrast in performance could be explained by slight differences in the analysis setup; RPs were computed from 2-second, while CNVs from 3-second EEG epochs. Also, due to experimental design, train-test split for RP was 180-60 compared to 210-30 in case of CNV. Notably, the proposed analysis pipeline is comprised only of steps that can be directly adapted to a real online setting. Even though initial performances are modest, they are expected to increase over time once subjects are provided online BCI feedback and learn to modulate their neural patterns [3]. We will also report results of such closed-loop BCI experiment during the conference.

Significance: Our results indicate that slow cortical potentials can be detected with a confidence over chance level utilizing Riemannian geometry and template matching. The adaptive re-centering step facilitates robust and reliable performance over multiple sessions. The proposed method shows promise as a useful tool for future BCI applications aiming on movement preparation and RP and/or CNV detection.

Acknowledgments: This work was partially funded by the Charley Sinclair Foundation.

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Exploring the Impacts of Longitudinal BCI Training for Power Mobility in Children with Physical Disabilities

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Introduction: BCI learning, in which the user learns to generate brain activity that results in a desired device behavior, is a determinant to successfully operating BCIs [1]. Children with severe neurological and physical disabilities (e.g., quadriplegic cerebral palsy) are capable of using EEG-based BCI systems [2]. However, it is unknown how the plastic brains of such children may change over time in response to BCI training [3,4]. We are aiming to characterize neural mechanisms of functional changes in children with severe physical disabilities as they learn to control a BCI-operated power mobility system.

Material, Methods, and Results: One pediatric patient (male, age 11) with quadriplegic cerebral palsy has been analyzed within a large multi-site longitudinal study. The BCi-Move trial includes a structured training program in which pediatric participants with severe quadriplegic cerebral palsy learn to operate a power mobility wheelchair over 12 weekly sessions using a mental-command based BCI. Continuous EEG recordings were collected using the EPOC Flex Cap (EMOTIV, United States), a commercially available 32-channel headset with saline electrodes, of which 14-channels were selected for compatibility with the Emotiv Cortex Engine. Functional connectivity was analyzed via imaginary part of coherency (iCOH) from EEG data collected from participant training of a "neutral" mental command, a learned skill representing a state in which no purposeful mental activity occurs (Fig. 1A). A minimum spanning tree (MST) was then calculated (Fig. 1B), with graph theory metrics (average degree (AD), betweenness centrality (BC), average shortest path length (ASPL), and global efficiency (GE)) used to characterize network changes occurring across BCI learning sessions (Fig. 1A). These characteristics were then compared to behavioral performance. The resulting networks were successfully estimated and compared between the first (AD: 0.9, GE: 0.40, ASPL: 3.41) and last sessions (AD: 1, GE: 0.44, ASPL: 2.83).

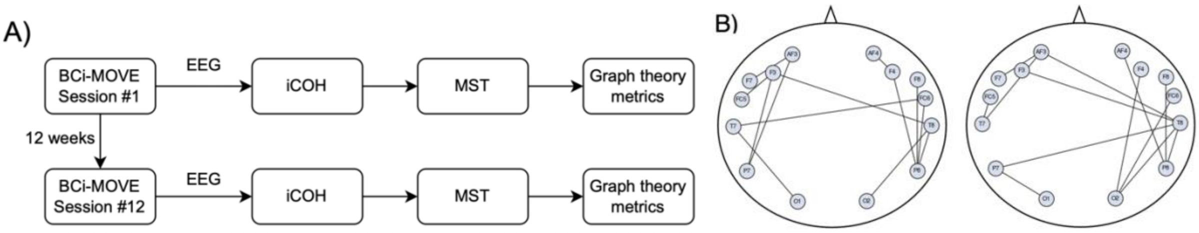

Figure 1. A) Methodology of analysis. B) *Binary graphs obtained via MST of participant during session 1 (left) and 12 (right).*

Discussion: These preliminary results support feasibility and provide an overview of an analysis pipeline for using network analysis to explore EEG-based mechanisms of BCI learning in children with severe disabilities participating in a longitudinal clinical training program. Understanding how functional networks reorganize with longitudinal BCI training in children with quadriplegic cerebral palsy may reveal patterns in functional network changes that correlate with BCI performance.

Significance: Despite BCI-learning being a core driver of success in BCI use, the mechanisms underlying BCI-learning in children with severe physical disabilities have not been explored. This novel study will investigate how functional reorganization of the brain occurs in children with severe physical disabilities during continuous BCI training.

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Labeling mental fatigue for passive BCI applications: Accuracy vs applicability tradeoff

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Introduction: Within BCI research, particularly passive-BCI (pBCI) research, mental fatigue estimation is of great popularity, as mental fatigue can be attributed to catastrophic events in risky work settings (e.g. aviation and nuclear plant domains). Mental fatigue is often understood as a psychobiological mental state, caused by prolonged cognitive activity resulting in an increased probability of a performance decrement [1]. The most popular method to label brain activity data is time-on-task (TOT)**.** In practice, data are often labeled using the first and last blocks of an experimental procedure for binary classification between non-fatigued and fatigued states [2]. While these approaches often yield high classification accuracies, their usefulness in practical applications is debatable, as the classification is not directly linked to the behavior of the user. A more applicable approach may be to move towards performance estimation in the context of mentally fatiguing environments. Another aspect to consider is that using the entire frequency spectrum of the EEG signal may inflate classification accuracies, due for instance to different motor activity between conditions which generates different amounts of artifacts within epochs and trials. This study has been designed to directly assess the impact of the type of mental fatigue labeling on estimation accuracy using a surveillance task dataset. In addition, the impact of the range of frequencies used for estimation is also considered. We hypothesize that TOT labeling as well as using the entire EEG frequency spectrum will result in a more accurate classification as compared to using performance estimation and a restricted EEG frequency spectrum.

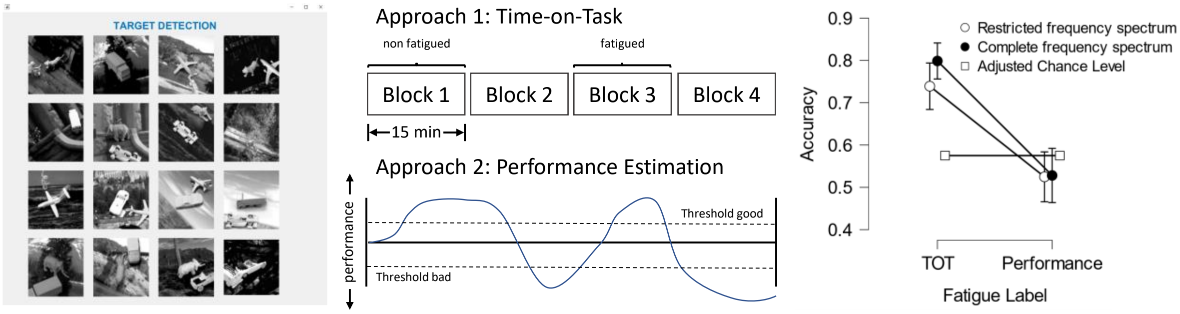

Figure 1 (from left to right) Screenshot of the visual search task in which participants had to detect humans to launch a rescue. | Comparison of the two labeling approaches | Results of the analysis, showing the upper limit of the confidence interval for chance level (57.5%) according to [3].

Methods: Data from 13 participants performing a 60-minute visual search task was recorded using a 64-electrode EEG setup. The data was preprocessed, either filtering out any motor-related activity (>20 Hz) or keeping the entire spectrum (only a 50 Hz notch filter). The data was labeled using one of two approaches. The TOT approach used the first and third (out of 4) blocks. The second approach used behavioral performance to label the epochs. Data were then classified using a Riemannian minimum-distance-to-mean classifier. Accuracies were compared using a 2x2 ANOVA.

Results: Classification accuracies obtained using TOT labeling were significantly higher as compared to performance labeling ($F(2,48)=89.87$ $p<0.001$). While the difference between the two spectra used in this approach was not significant, using the entire frequency spectrum still resulted in an almost 6% increase (79.9% vs 73.9%) in accuracy.

Discussion: As shown by these results, performance estimation is significantly more challenging as compared to TOT estimation. However, for real-world applications, TOT labeling has no real added value compared to actually knowing how much time has been spent on a task, whereas performance labeling presents more use cases for instance in order to predict and mitigate degraded attentional states via adaptive interfaces based on a pBCI [1].

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Lessons learned on Implantable BCIs for Home Use

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Introduction: The Utrecht NeuroProsthesis (UNP) study aims at accomplishing independent home use of an implantable BCI for communication by individuals with locked-in syndrome (LIS). Although conducting research on home use of implantable BCIs is highly complex, the eventual successful clinical implementation of the technology will rely on sharing of procedures and experiences of ongoing studies, which typically include only a limited number of participants. We have recently described the methodological considerations that should be taken into consideration for studies on implanted BCIs, based on our experience during the UNP study [1]. Here we report on several, sometimes anecdotal, observations we made during the long-term collaborations with the UNP participants, and that may be relevant for the assessment of the effects of environmental and user-related factors on performance of an implanted BCI.

Material, Methods and Results: Three people with LIS (UNP1, UNP4 and UNP5) have received the UNP implant. Electrodes were placed over the sensorimotor hand area and connected via subcutaneous leads to an implanted amplifier/transmitter device that was placed in the sub-clavicular area. From our limited sample, we noted that LIS etiology may influence the spectral features underlying the BCI control signals, as reported in [2], and that the dynamics of these spectral features during the night requires dedicated decoders for nocturnal BCI use. We also noted that residual movements, sensory stimulation of the hand, as well as attempted movements of several other body parts, such as foot and eyes, can activate the same region as attempting to control the hand. Surprisingly, external sources of perturbations, such as during vehicle transportation, driving on cobblestones, and use of mechanical ventilation, seemed to influence the signal as well. Finally, two subjective reports of the participants are also worth noting. First, there seems to be some limit to the speed at which a user can attempt to move, and practice seems to increase the speed at which movement can be attempted. Second, all participants agree that attempting movement of the hand requires focus. For example, UNP1 reported on several occasions that effort is higher when her hands are cold, or when her hand is not positioned 'properly'.

Discussion and significance: In general, it is important to ask for the user's opinion about a BCI system on a regular basis since subjective experiences can affect the perceived usability of a BCI system. We believe that sharing not only quantitative scientific results and methodological considerations, but also any interesting incidental findings and subjective observations may contribute to defining important topics for more detailed investigation with more participants, eventually leading to improved standardization, and effective clinical implementation of (implanted) BCIs.

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Neural network transfer learning with fast calibration for mental imagery decoding

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Introduction: A typical decoding challenge faced with brain-computer interfaces (BCI) is the small dataset size compared to other domains of machine learning like computer vision or natural language processing. A possibility to tackle this lack of training data is through transfer learning, but this is non-trivial because of the non-stationary of EEG signals. Consequently, explicit calibration phases at the start of BCI sessions are usually required.
In this study, we show how a deep neural network can be used in the context of motor imagery transfer learning, while still allowing for a session-specific calibration phase and without a computationally expensive model fine-tuning.

Methods, Materials and Results: We introduce a simple domain adaptation technique. It first learns an embedding (i.e., abstract vectorial representation) across subjects to deliver a generalized data representation. It then feeds the embeddings into subject-specific or session-specific simple classifiers. The embedding functions were obtained by training EEGNet [1] using a leave-one-subject-out (LOSO) protocol, and the embedding vectors were classified by the logistic regression algorithm. We conducted offline experiments on multiple motor imagery datasets from the MOABB library [2]. Our pipeline was compared to two baseline approaches: EEGNet without subject-specific calibration and the standard Filter-Bank Common Spacial Patern (FBCSP) [3] pipeline in a within-subject training.

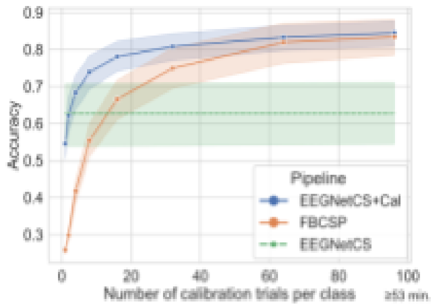

Figure 1. Classification accuracy of the different pipelines on the High Gamma Dataset [4].

Discussion: We observed that the representations learned by the embedding functions were non-stationary across subjects, justifying the need for an additional subject-specific calibration. We also observed that the subject-specific calibration improved the score. Finally, our data suggest, that building upon embeddings requires fewer individual calibration data than the FBCSP baseline to reach satisfactory scores.

Significance: Our method allows to use deep learning and all its recent advances for EEG decoding while still having a session-specific calibration in a reasonable time.

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ROS-Neuro, a common middleware for neural interfaces and robotic applications

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Introduction: The last years have seen great technological advancements in the field of neural human-machine interfaces (HMI) to control robotic devices [1]. However, the uptake of these technologies in real-world applications represents a challenge still unmet. The reasons are three-fold: (i) lack of a common development platform to facilitate the sharing of methods among the scientific community; (ii) lack of well-defined common standards, leading to heterogeneous and home-made solutions; (iii) lack of common technical tools to integrate neural interfaces and robotics, thus neglecting the potential benefits of introducing existing artificial intelligence (AI) solutions in neurorobotic applications.

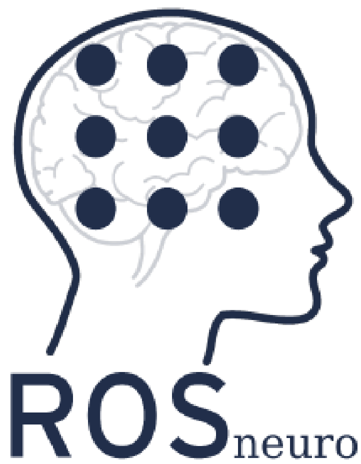

Fig. 1 ROS-Neuro logo

Materials, Methods and Results: We spotlight ROS-Neuro, the first middleware explicitly designed for neurorobotics, based on the Robot Operating System (ROS), the software framework for robotics now a *de facto* standard [2]. ROS-Neuro exploits the modularity and the standard communication infrastructure of ROS to develop all the components required by a closed-loop neural interface (i.e., acquisition, processing and decoding). These are implemented at the same conceptual and implementation level of the software controlling the robot. ROS-Neuro provides interfaces, in the form of ROS packages, for neurophysiological signals acquisition and recording from several EEG and EMG commercial amplifiers, as well as the possibility to integrate custom biosignal acquisition systems [3]. The current version of ROS-Neuro includes also standard modules for implementing the most common processing algorithms (e.g., temporal, spatial filters) and provides a graphical interface for visualizing in real-time neural signals at the different steps of the processing pipeline.

Discussion: ROS-Neuro is distributed fully open source (https://github.com/rosneuro) as this project aims at creating a wide community sharing the latest advancements in HMI and robotics, exploiting ROS-Neuro as a robust and flexible ecosystem to evaluate and compare different approaches.

Significance: We firmly believe that the use of ROS-Neuro as a common development platform for the community represents the key for boosting the performance of neurorobotic technologies and pave the way for their use in the everyday life to improve the quality of life of people with disabilities.

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Introducing design ideas for an interactive BCI online forum with a mixed-method qualitative and quantitative approach

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Introduction: Brain-computer interfaces (BCIs) can enable non-muscular communication and control for severely paralyzed people. However, efforts that directly involve potential end-users and address their individual needs are scarce, resulting in a prevailing translational gap [1, 2]. To help bridging this gap, it has been proposed to implement a BCI-specific online forum to sustainably strengthen the interaction between scientists and end-users [3]. The aim of our study was to explore the usefulness of and concrete design ideas for a BCI-specific online forum based on an interview/questionnaire approach involving paralyzed end-users and BCI Society members.

Material, Methods and Results: In this study, 6 severely paralyzed end-users were interviewed and 121 BCI Society members completed a survey about their wishes, suggestions, and opinions regarding a BCI-specific online forum. Data were analyzed with a mixed-method qualitative and quantitative approach [4]. Even though they already felt integrated into the scientific process on a medium to high level, all 6 end-users indicated various unmet needs and provided concrete ideas on how a BCI-specific forum could be a valuable tool. Among the BCI Society members, 101 of 121 expressed support for a BCI-specific forum. Table 1 lists selected design wishes and potential pitfalls to be avoided.

Table 1. Selected forum design wishes and pitfalls to be avoided as reported by 6 paralyzed end-users and 121 BCI Society members.

Design ideas	**… from paralyzed end-users**	**… from BCI Society members**
1st highest rated wish	More systematic exchange with scientists (focusing on what is (not) needed for everyday life, …)	Providing resources for users and scientists (hardware and software tutorial collection for caregivers, juniors, …)
2nd highest rated wish	Access to resources and information (hardware and software tutorial collection for caregivers, …)	More systematic exchange with other scientists (everyday question threads to complement traditional exchange…)
3rd highest rated wish	More systematic exchange with other users (BCI forum to complement disease-specific forums, …)	More systematic exchange with users (more direct integration into research process, “participant pool”, …)
1st highest rated potential pitfall	Accessibility should not be too complex (unflustered alternative to social media overload, …)	Organizational efforts should not be underestimated (“easy to create, but difficult to keep up to date”, finances, …)
2nd highest rated potential pitfall	Data privacy should not be violated (forum as a private space exclusively for registered users, …)	Scientists should not have concerns to participate (potential for theft of ideas in competition for scientific impact, …)
3rd highest rated potential pitfall	Non-English speakers should not be excluded (integration of language specific forum threads, …)	Unique selling points should not be neglected (distinct differentiation from other forums and social media, …)

Discussion and Significance: As exemplified by the selected ideas in Table 1, concrete BCI-specific online forum design aspects could be identified. At the International BCI Meeting 2023, we want to discuss these and further design wishes and potential pitfalls, such that the forum can serve as a meaningful resource for the BCI community, contributing to the meeting’s motto “Balancing Innovation and Translation”. In a broader sense, this work complements previous interview/questionnaire studies [5, 6] and further promotes user-centered design for BCI optimization [7, 8].

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Measuring presence in a virtual environment using electroencephalography: A study of breaks in presence using an oddball paradigm

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Introduction: Presence is one of the main factor conditioning the user-experience in virtual reality (VR). It corresponds to the illusion of being physically located in a virtual environment [1]. Presence is usually measured subjectively through questionnaires. However, questionnaires cannot be filled in when the user is experiencing presence, as it would disrupt the feeling [2]. The use of electroencephalography (EEG) to monitor users while they are immersed in VR presents an opportunity to bridge this gap and assess presence continuously. This study aims at investigating whether different levels of presence can be distinguished from EEG signals.

Material, Methods & Results: We immersed 18 participants in a VR environment using a Head-Mounted Display (HMD). Our participants experienced two experimental conditions: 1) a continuous experience in VR and 2) a VR experience where their feeling of presence was negatively affected by an abrupt presentation of the real environment inside the HMD (i.e. breaks in presence [3]). While our participants were within the virtual environment, they were presented with an oddball paradigm, i.e., sequences of repetitive sounds, infrequently interrupted by a deviant sound (20% of all stimuli) played on loudspeakers.

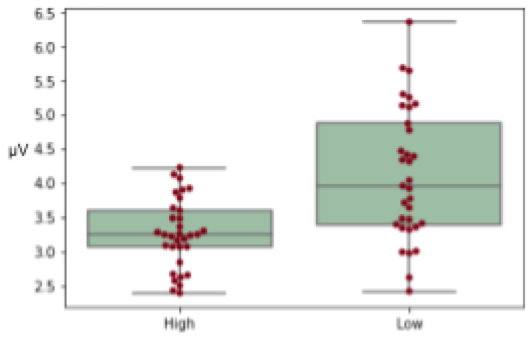

Fig.1: Average P300 amplitude across subjects recorded from 270 to 340 ms after each deviant stimulus for the High and Low presence context.

We focused our EEG analysis toward the reaction to the deviant stimuli, as this reaction modulates the amplitude of the P300. Preliminary results indicate a significant difference in the amplitude of the P300 between the high and low presence context (Figure 1). When a subject is in a low presence context (condition 2), the P300 is higher in amplitude, reflecting a higher attention to the real environment (hence a lower presence in the virtual environment).

Discussion: This study shows that electroencephalography can be used to assess presence using an oddball paradigm. However, the use of oddball sounds can impact the feeling of presence for some users. Future works should propose new kinds of less disruptive stimuli.
Significance: We propose here a new objective and less intrusive way to continuously measure presence in a VR environment.

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Interpersonal Physiological Synchrony based BCI: A Perspective

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Background: Interpersonal physiological synchrony (PS) refers to simultaneous changes over time in a physiological signal recorded from multiple individuals. PS and other forms of associations between signals across individuals have been examined in the context of social relationships and communication. An expected important instigator of PS is that individuals attend to the same external events. Following this principle, we started to work on PS from the viewpoint that PS is a potentially useful marker of attentional engagement to external events. Advantages of PS as a marker are that it does not require labeled, personal training data (as in many other brain-based methods to monitor attention) and that it may be used in real life circumstances where onsets of potentially relevant stimuli are not known. Besides PS in EEG, we examined PS in heart rate and electrodermal activity to potentially augment or even replace the information coming from EEG. This would facilitate recordings in real life. Over recent years, we and others found that PS in EEG, heart rate and/or electrodermal activity varies as a function of attentional instruction [1], as a function of trait-based attentional bias [2] and is also increased by stimuli that are expected to draw attention in a bottom-up way [3]. High PS predicts high cognitive performance [1,4] and PS can be determined using electrodermal activity and heart rate wearables in real life settings [5], signifying the potential practical relevance and feasibility of PS as measure of attentional engagement.

Physiological Synchrony BCI: While it is possible to determine PS in (near) real time, and open-source algorithms for this are already available [6], we are not aware of studies that aim to boost cognitive performance by adapting a system in real time utilizing PS-based information about attention. We think that such PS-BCIs for enhancing cognitive performance may be feasible and valuable, especially in digital education, high cognitive workload, or high vigilance settings, . We outline possible design and usage of different types of PS-based information (at the level of the individual with respect to the group; at the level of the group as a whole), different types of interventions (providing information to the student; adapting a virtual teaching system; providing information to a human teacher) and the ethical considerations associated with these possible applications. We end with stating the most essential open research questions.

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Generalization across participants in continuous hand trajectory decoding

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Introduction: One of the challenges in the BCI field is to achieve a decoding model that can be employed in an unseen participant without the need to tailor the model with participant-specific calibration data. It would significantly improve a BCI's usability by saving the time to acquire the calibration data. In this study, we investigated such a scenario in the context of hand trajectory decoding from EEG.

Material, Methods and Results: We utilized a dataset with 10 participants [1] with 3 sessions of measurement. Participants followed a target on the screen with their dominant hand, but the hand's movement was restricted. The online visual feedback was realized for each measurement block by mixing different percentages between the target and the EEG decoded position in 2D (0%, 50%, and 100% EEG). A partial least squares (PLS) and a square-root unscented Kalman filter (SR-UKF) were trained with 2 types of features from EEG signals: sensor-space and source-space signals extracted according to the averaging method described in [2]. The decoder was trained with data from the 0%EEG block, i.e., simulated feedback, of session 1 in a leave-one-participant-out (LOPO) manner and applied to every measurement block without any update. A recursive exponential weighted PLS (REW-PLS) [3] was utilized to overcome the memory limitation due to the large pool of training data. Figure 1 illustrates boxplots of group-level correlation with a 95% upper bound chance level from the shuffling approach plotted as black lines. The median correlations were less than 0.1 in every case, regardless of the type of features. There were no clear observable trends when considering the correlation in a time progression manner.

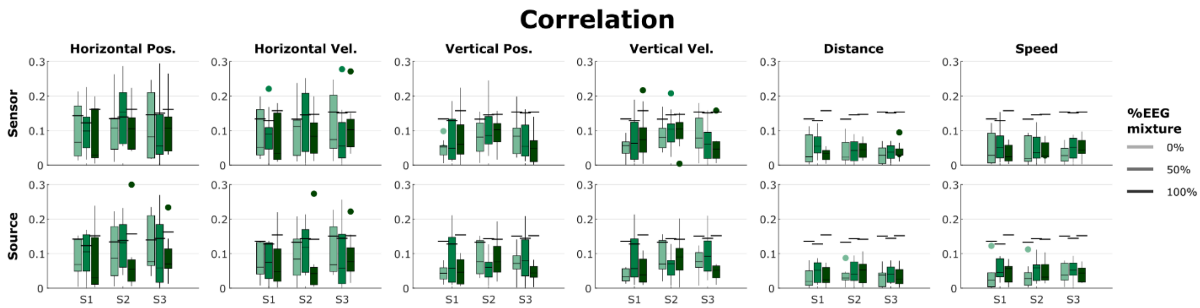

Figure 1. *Group-level correlation of 0%-100%EEG blocks from sessions 1 to 3 (S1-S3). Upper row: sensor space results, lower row: source space results. Dots show outliers. Black bars indicate the chance level.*

Discussion: The correlations suggested that the decoder could not be generalized well enough to perform above chance level in unseen data. Note that the attempted movement was typically reported to have a lower correlation than the executed, so this could reduce the generalization capacity of the decoder.

Significance: Despite less-than-chance results, this is the first step to examining the generalization of hand movement decoding from EEG, which will be further expanded in the subsequent study.

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The influence of pitch modulation on the performance of a BCI-based language training system.

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Introduction: Aphasia is a language impairment observed, e.g., after a left hemispheric stroke, that has a substantial impact on patients' quality of life. In the chronic period, conventional language training methods unfortunately have limited to no effect. We have proposed a new intensive (30 hours, multiple sessions per week) language training using a brain-computer interface (BCI), which revealed significant and lasting improvements of multiple language aspects when tested on ten patients with chronic aphasia [1]. Six loudspeakers surrounding the subject's head were used in this training to deliver spatially distributed word stimuli of a six-class auditory oddball protocol. While it is desirable to translate the training in the future into offices of local practitioners or to patients' homes, installing the six loudspeaker arrangement there may be prohibitive. To prepare a later headphone-based setup and resolve front-back confusions typically observed in simulated sound directions, we explore the influence of pitch modulation of word stimuli.

Material, Methods and Results: We compared the ERP effects of the conventional spatial loudspeaker setup (6D condition) with a condition that enriches word stimuli by pitch modulations expected to help subjects determine the spatial direction of a presented word (6D-Pitch). Seventeen native Dutch speakers participated in the experiment. A Dutch sentence, whose last word was missing, cued the target word from one of the loudspeakers. Subsequently, a pseudo-random sequence of 90 word stimuli per trial was delivered. While the target word matched the previously presented sentence, the other five did not. Subjects were requested to pay attention to this target word. This abstract reports on two (6D and 6D-Pitch) out of overall four conditions delivered in a single session. In 6D, all sounds were played at the same pitch; in 6D-Pitch, sounds played from the front and back were played at a higher and lower pitch, respectively. Sixty-four channels of EEG and vertical EOG of the right eye were measured. Per subject and condition, the ERP responses to targets and nontarget were averaged over trials before computing the grand average ERP response over subjects. In addition, the binary classification performance using ToeplitzLDA [2] and a BCI simulation (choosing one out of six classes) were investigated using 4-fold chronological cross-validation.

Grand average ERPs showed only minor differences between the 6D and 6D-Pitch conditions. Compared to word ERPs of healthy subjects reported in [1] we observed a higher P300 amplitude ($1.8\ \mu V$ vs. $1.3\ \mu V$), which could have been caused by slightly different preprocessing. The mean binary target vs. non-target classification accuracy (AUC) was 0.745 for 6D and 0.747 for 6D-Pitch (not significant). On the other hand, the mean accuracy (chance level = 0.167) for choosing one out of six words based on 15x6 epochs was slightly higher (not significant) for 6D-Pitch (0.868 vs. 0.850).

Discussion: Pitch-enriched cues are known to help resolve front-back confusions in spatial sound presentations. Thus pitch information might be important also for the user acceptance of a future headphone-based training setup with simulated sound directions. As our current study revealed that additional pitch cues do not impede the classification performance in the loudspeaker condition, we expect that no substantial performance drop will be observed for incorporating pitch information also in a future headphone condition, which would allow for a substantial simplification of the current loudspeaker-based aphasia training setup [1].

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Neural correlates of continuous feedback processing during the execution of a 2D driving task

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Introduction: Recent research of our group unveiled strong modulations akin to an error-related negativity (ERN) and error positivity (P_e) in the electroencephalogram (EEG) when faced with a continuous deviation of feedback from the intended target [1]. To answer two open questions – whether these modulations were induced in part by periodic visual input, and if the ERN- and P_e-like scalp potentials arise independently from each other in a phase-lock with the underlying error signal – we proposed a new paradigm. Within EEG measurements in 10 participants, we argue that the modulations are indeed feedback-related and that our observed potentials arise independently at distinct phases of the feedback-target deviation.

Material, Methods, and Results: EEG signals (60 channels, 10-10 system) of ten participants (7 female, 1 left-handed) have been recorded in pairs as one participant (Operator) executed 2D steering tasks while the other (Observer) observed their performance. Consecutively, four paradigm conditions were presented in 3 3.5-minute runs each. During the winding road condition, participants observed a self-driving car moving perfectly along a winding road while the Operator steered along. In three control conditions (full, erroneous (distinct/indistinct)), the Operator had first full, then limited steering control and was instructed to always stay on the white centerline. During erroneous control conditions, the car was then automatically moved away from the centerline as soon as it steered too close, leading to continuous deviations from the road. Following eye artifact removal and removal of front-most electrodes [2], bandpass-filtering (0.2-10Hz), and bad channel interpolation, data were re-referenced to their common average and epoched around [-3,3]s of a local maximum in deviation from the road (see Fig. 1).

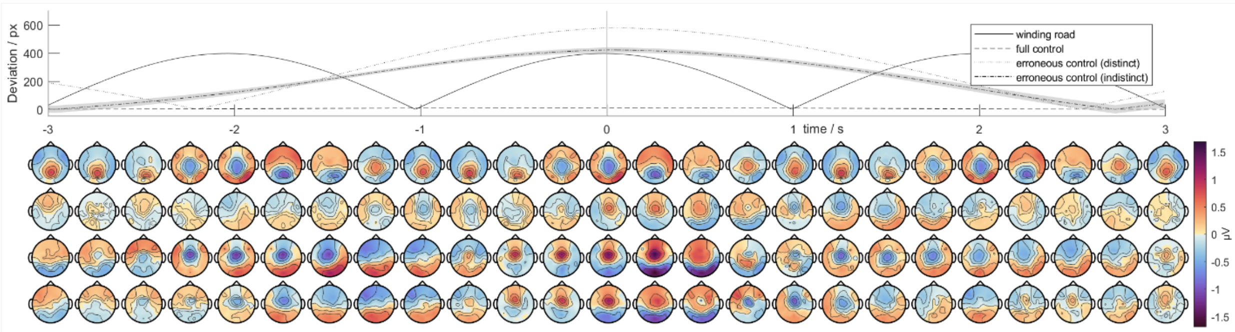

Figure 1. *Grand average car deviation from the road* ***(top)*** *and grand average topographical maps* ***(bottom)*** *for the four conditions* winding road, full control, erroneous control (distinct/indistinct) *from top to bottom.*

Discussion: For all conditions, we observed clear modulations above parieto-occipital (winding road) and fronto-central (control) areas in the EEG corresponding to modulations in the feedback-target deviation, implying that the processes modulating with the visual input and the feedback processing are indeed distinct. Further, temporal distances of around 2s between ERN- and Pe-like scalp topographies promote that these correlates lock to distinct phases in the deviation signal, rather than a common event, as usually seen in discrete error processing literature [3].

Significance: The existence of neural correlates to continuous rather than discrete inputs demanding error/feedback processing, as well as the clear scalp topographies observed, promote new prospects regarding the instant correction of brain-computer interface tasks involving fine-tuned feedback control. As a next step, algorithms for classification or regression of the continuous feedback signal from the EEG may be worth exploring.

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Speech perception in the sensorimotor cortex: A potential source for false positives during speech-BCI control?

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Introduction:

Recent advances in speech decoding from the sensorimotor cortex (SMC) have demonstrated the potential of using this area for BCI control based on (attempted) speech movements [1,2]. However, the SMC has been found to also show increased activity during speech perception [3,4], which is a potential source of false positive activation of a speech-BCI. This study investigates the overlap between speech perception and speech production activity patterns in the SMC and evaluates decoding performance during speech perception.

Material, Methods, and Results:

Four patients with epilepsy were subdurally implanted with high-density (HD) electrocorticography (ECoG) grids over the left SMC. Participants completed an audiovisual speech perception task, and a speech production task in which they had to speak out loud the same syllables (7 syllables repeated 10 times). Speech trials were alternated with rest. After preprocessing, high-frequency band (HFB, 65–95 Hz) power was extracted from the ECoG data. The HFB response during speech trials was compared to that during rest using R^2 analysis. Each electrode with a significant response to speech compared to rest was labelled as responsive to perception, production, or both. This analysis showed that both speech perception and production generate increased HFB responses in overlapping areas of the SMC. Plotting the R^2 values of the two tasks against each other revealed that electrodes with high R^2 values during production tend to also have high R^2 values during perception. To test whether speech perception is a source of false positives during BCI control (i.e., perception trials classified as produced words), a classifier was trained on the production data, and subsequently tested on both production and perception data. While the classifier trained on production data could reliably decode produced speech sounds, it also generated false positives when tested on speech perception data for all four subjects.

Discussion and Significance:

The current study confirms earlier findings on the presence of speech perception related activity in the SMC [3,4], and indicates that decoders of speech production may generate false-positive responses during audiovisual speech perception. This topic deserves further investigation before speech BCIs can be used reliably in naturalistic situations.

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EEG Oscillatory Correlates Of Aesthetic Experience – A Review

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Introduction: With an aestheticization of life through technology, as well as with advances in neuroimaging and personalized marketing, the field of neuroaesthetics, i.e. the neuroscience of aesthetic experiences (AE), has received increased attention. An AE can be defined as "a perceptual experience that is evaluative, affectively absorbing and engages comprehension (meaning) processes" [1]. Previous neuroaesthetic reviews mostly focused on fMRI and ERPs and the neural dynamics of aesthetic preference remain unclear [1]. Therefore, we reviewed potential EEG oscillatory neuromarkers of AE from studies investigating brain oscillations of visual art preference. In order to avoid philosophical debate on the being of Art, we define 'art' pragmatically and consider as 'art', objects that are culturally accepted as 'art'.

Material, Methods and Results: We conducted a literature review by scrounging publicly available databases, as well as the references and citations of neuroaesthetic literature. For search queries we used "+aesthetic|art|painting +EEG|brain|neur* +oscil*|wav*|frequen*| rhythm*". We used similar expressions in German, French and Spanish. We included EEG studies investigating oscillatory correlates of AE with static visual art stimuli (i.e. paintings and photographs) in 'naturalistic' viewing conditions (e.g. no Oddball paradigms), in order to reduce potential confounding factors. We rejected studies that did not collect aesthetic judgments from subjects. Our search yielded 6 articles fulfilling the criteria. 3 experiments (1 in the lab, 2 in the wild) reported frontal alpha asymmetry to be correlated with aesthetic beauty ratings [2, 3, 4]. [5] discovered evidence of occipital and parietal alpha suppression for preferred binarized Pollock paintings. Another mobile experiment found frontal beta suppression to be indicative of favorite paintings in a museum [6]. The last study described increased centroparietal high gamma for aesthetically moving visual art [7].

Discussion: The reviewed articles reported inconsistent modulations in alpha, beta and gamma frequency bands correlated to visual art preference. The inconsistencies might be explainable by the different types of aesthetic judgment or by muscle artifacts confounds. More reproducible naturalistic studies with good EEG preprocessing and artifact removal protocols are needed for deeper scientific understanding of AE.

Significance: This review summarizes EEG correlates of AE that could be used in passive BCI to improve user experience, e.g. by personalizing the aesthetics of digital environments.

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Decoding single and paired phonemes using 7 T functional MRI

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Abstract

Brain-computer interfaces (BCI) can provide a means of communication for people suffering from locked in syndrome. Several studies have shown that motor programs related to individual phonemes are represented in detail in the sensorimotor cortex. This would theoretically allow BCI able to decode continuous speech by training classifiers using the activity underlying production of individual phonemes.

One way of determining cortical representation is high field functional MRI that samples the brain at high resolution without gaps. We assessed the decodability of trials with individual and paired phonemes (pronounced consecutively with one second interval) using activity in the sensorimotor cortex. Fifteen participants pronounced 3 different phonemes (/t/, /p/, /ə/) and 3 combinations of two of the same phonemes (/p/ /t/, /ə/ /t/, /p/ /ə) in a 7 T functional MRI experiment.

Individual and paired phonemes were classified using linear support vector machines (SVM) with a classification accuracy of 47% (17% chance level). To assess if it is possible to decode individual phonemes from the paired combinations of phonemes, classifiers were trained on single phonemes and tested on paired phonemes achieving a classification accuracy of 53% (33% chance level). A SVM searchlight analysis showed that phoneme representations are distributed across the ventral sensorimotor cortex.

Our study demonstrates that activity of isolated phonemes is present and distinguishable in combined phonemes with high field fMRI. These findings suggest that speech BCI with machine learning algorithms trained on individual phonemes may be a feasible strategy for intracranial electrode grids.

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Distinct brain potential of balance perturbation and error processing

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Introduction: The maintenance of balance is a complicated process in the human brain, which involves multisensory processing. Neuroimaging studies showed that a specific cortical activity called perturbation-evoked potential (PEP) appears in EEG during balance perturbation [1]. PEPs are primarily recognized by the N1 component localized in the fronto central regions. In this study, we tested whether the N1 is an indicator of the cognitive error processing by imposing two types of perturbations consisting of error and correct perturbations.
Material, Methods and Results: Fifteen participants sat in a glider, and they were tilted to the left and right directions by using KUKA KRc1 robot. Tilting direction was shown on the screen 2-4 s before the balance perturbations to inform the participants about the direction of the upcoming movement. At some rare cases of the experiment, participants were exposed to an opposite direction of the expected/shown direction, which was considered as error perturbation. A schematic of the experiment is depicted in Figure 1a.

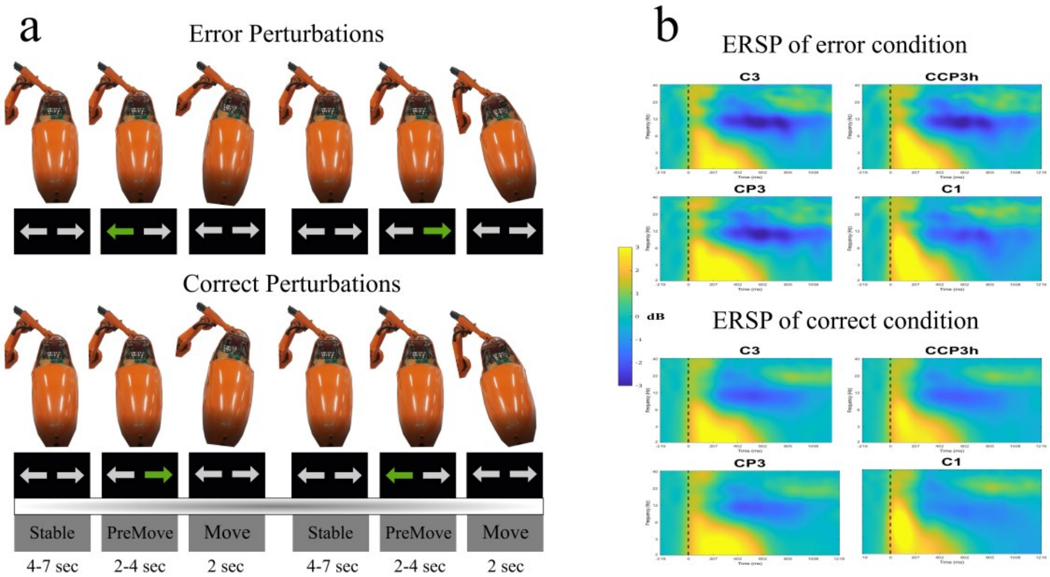

Figure 1. *Experimental setup and results. The glider was tilted to left and right directions (Panel a). Averaged ERSP plots of 15 participants scaled power in dB were displayed for channels C3, CCP3h, CP3 and C1 (Panel b).*

We measured EEG signals using 63 active shielded Ag/AgCl electrodes (ANT-neuro) with a sampling rate of 512 Hz. EEG data were bandpass filtered between 0.5 and 40 Hz, then we extracted 2-s epochs (-0.5 to 1.5 s) with respect to perturbation onset obtained from accelerometer data. To assess the neural correlates of error and correct perturbations, we calculated and plotted event-related spectral perturbation (ERSP) by using the inter-trial variance (Figure 1b). In this way, we unmasked the effect of the PEP from EEG (de)synchronization. Next, we performed the cluster-based permutation test, corrected by a 2000 random permutation test with a $p = 0.025$.
Discussion: The results shows that a (de)synchronization happened in the time period of 0-0.5 s, and 0.5-0.8 s for both conditions. Spectral suppression of alpha band was significantly different in error condition over central regions. This phenomenon is named error-related alpha suppression (ERAS) [2], and it is associated with conscious sensations of error. No differences were observed between error and correct perturbations in the time range of N1 potential.
Significance: Our findings indicated that early cortical responses of balance perturbation are not associated with neural error processing, and errors induce distinct cortical responses that are distinguishable from brain dynamics of N1 potential.

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Towards Adaptive Gait Generation for BMI-driven Lower Limb Exoskeleton

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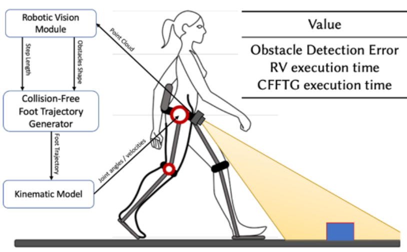
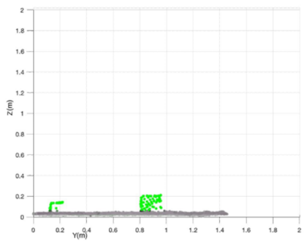
Introduction and Significance: Powered lower-limb exoskeletons (LLEs) represent a recent assistive technology to allow people with gait impairment to regain the capability of walking [1]. However, despite the recent advancements that this technology has seen in the last 30 years, the use of powered exoskeletons is still restricted to clinical settings or to highly controlled environments [2]. Two reasons can be identified for this limitation: first, LLEs usually employ pre-programmed walking patterns [3]. Second, LLEs do not consider the environment in which walking occurs. To overcome this limitation, the proposed solution employs shared autonomy with respect to the task of adaptive gait generation, with the goal of avoiding obstacles or unfeasible foothold positions.

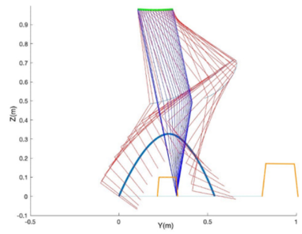
Materials, Methods and Results: An RGB-D camera (RealSense D-455) is mounted on the exoskeleton pelvis and a Robotic Vision module is implemented for detecting ground plane and obstacles and computing the next foothold position taking into consideration robot state, obstacles' shape and safety constraints. In addition, a novel iterative-based collision-free foot trajectory Generator (CFFTG) and a parameterized gait kinematic model are proposed to compute hip and knee joints' angles that are sent to the robot controller to produce a feasible gait pattern allowing to avoid the detected obstacles (Figure 1a). Six repetitions have been carried out by simulating a situation where the LLE was challenged to surpass different obstacles: following a hardware-in-the-loop approach, point clouds were acquired with the RGB-D camera to test the Robotic Vision module on real data, and based on the detection a simulated version of the environment was produced to test CFFTG and kinematics. The solution was able to detect 100% of the obstacles with a mean spatial error of 0.35±0.25 cm, and to perform the correct action (i.e., executing a step or aborting it when unfeasible); additionally, execution times never exceeded 150 ms, which would allow the solution to be used in real time applications (Figure 1b-d).

Discussion: Future work will focus on adding a brain-machine interface module [4] to infer user's commands in real time by evaluating electroencephalography signals. Also, the proposed solution will be implemented and evaluated by an healthy population and end-users.



Value	Mean
Obstacle Detection Error	0.35 cm ± 0.25 cm
RV execution time	61.48 ms ± 20.45 ms
CFFTG execution time	20.35 ms ± 5.73 ms





a) b) c) d)

Figure 1: a) A scheme of the proposed solution. b) Table with notable results. c) Detected Obstacles (Sagittal Plane). d) Kinematic simulation on MATLAB environment (Sagittal plane).

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N2pc-based decoding of covert visual spatial attention is independent of stimulus predictability

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Introduction: Recently, it has been shown that visual stimuli presented simultaneously in the periphery of the left and right visual hemifield are suitable to control a brain-computer interface (BCI) by shifting attention to a target stimulus with no requirement of eye movements [1]. In the electroencephalogram (EEG), parieto-occipital channels typically record stronger negative deflections around 220ms after onset of targets contralaterally presented compared to ipsilateral ones. The N2pc is defined as the difference of these contra- and ipsilateral EEG deflections. This phenomenon permits to decode the side of target presentation even though it is only covertly attended. Despite a huge body of literature on the effects of stimulus characteristics on the N2pc, the impact of stimulus predictability on decoding is not known. Here we investigate three facets of predictability of target stimuli on decoding accuracy and on EEG wave forms: presentation speed, temporal predictability and spatial predictability.

Methods: Twenty participants were asked to perform a visual search task in which they covertly attended a peripherally presented, colored target item. In each trial, a series of ten stimuli was shown, where the target and nontarget item were presented in opposite visual hemifields. In eight runs we combined different stimulus characteristics. We presented the items with shorter (600ms) and longer (800ms) stimulus onset asynchrony (SOA), with constant or jittered (0–250ms were added) SOA, and in a random or predictable (alternating between hemifields) order. We quantified the N2pc as difference between contralateral and ipsilateral event-related potentials, averaged between 180ms and 250ms and across channels P3, P7, PO3, PO7 and P4, P8, PO4, PO8, depending on the side of target presentation and compared these values using a paired t-test. Most importantly, we compared the decoding accuracies obtained by decoding the attended item from parieto-occipital EEG channels using an approach based on canonical correlation analysis [1], by means of Wilcoxon signed-rank tests.

Results: All three tested stimulus characteristics resulted in comparably high decoding accuracies, showing no statistically significant differences (random order: 90.3%; predictable order: 88.3%; short SOA: 90.0%; long SOA: 90.1%; constant SOA: 89.5%; jittered SOA: 89.2%). However, due to the faster stimulus, the information transfer rate (ITR) was significantly higher with short SOA (5.2 bit/min) than with longer SOA (4.0 bit/min). Waveform investigation resulted in a significantly higher N2pc amplitude with longer SOAs compared to shorter SOAs ($t(19)=5.14$, $p=0.0001$) and in random stimulus order compared to predictable stimulus order ($t(19)=3.96$, $p=0.0008$). No variation of the N2pc was found in jittered SOA compared to constant SOA.

Conclusion: Although the N2pc amplitude, as a marker of visual spatial attention, was significantly modulated when stimulation speed and spatial predictability was varied, no differences were found in decoding accuracy. The independence of temporal and spatial stimulus predictability shows that the N2pc represents a robust signal which can be used to control gaze-independent BCIs. While the higher ITR achieved with shorter SOAs suggests that the SOA could be further reduced, the length of the SOA is limited due to the subject’s cognitive capabilities and the time course of attention-based brain potentials.

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Cybersickness in Virtual Reality Neurofeedback Trainings

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Introduction: Virtual Reality (VR) serves as a modern and powerful tool to supplement neurorehabilitation, as well as neurofeedback (NF) and brain-computer interface (BCI) applications. To increase user motivation, adherence to training, or enjoyment, VR is increasingly used as visual feedback environment in BCI/NF applications[1]. However, between 20-80%[2] of all the users develop symptoms of cybersickness, such as nausea, oculomotor problems or disorientation during VR interaction. This raises the question of the extent to which cybersickness affects participants in the completion and success of the NF/BCI tasks. Hence, we investigated whether cybersickness inducing VR paradigms influence the success of a NF training task.
Material Methods and Results: 39 participants (mean age: 23.08 years; 51.3% female) had to complete a single electroencephalography (EEG) NF session consisting of seven feedback runs, in which they should increase their SMR (12-15 Hz) power while keeping Theta (4-8 Hz) and Beta (16-30 Hz) power as low as possible. Visual feedback was presented via an HTC Vive Pro VR goggle (see Fig. 1). Half of the participants received visual feedback in a VR environment inducing only slight cybersickness (constant VR). The other half received visual feedback in a varying VR environment, in which the field-of-view, camera angle and movement speed alternately changed, which strongly induces cybersickness. NF success was defined as an increase in SMR power across feedback runs. To investigate sickness, the simulator-sickness questionnaire (SSQ) had to be filled out before and after the session, furthermore the heart rate was acquired as an objective measure of sickness.
The results of a 2x2 ANOVA (factors group and early vs. late SMR) showed that in both, the constant and the varying VR environment, participants could increase their SMR power across the feedback runs ($F(1,36) = 9.11$, $p = .005$, $\eta_p^2 = .202$, see Fig. 2), but there were no group differences ($F(1,36) = 0.05$, $p = .830$). We could also show that sickness symptoms as assessed with the SSQ (2x2 ANOVA with factors group and pre-post-test) increased in both groups over the training ($F(1,37) = 57.10$, $p < .001$, $\eta_p^2 = .509$), but again there were no significant group differences ($F(1,37) = 0.82$, $p = .372$). The varying VR environment only led to descriptively higher SSQ values ($M = 40.31$, $SD = 24.43$) compared to the constant condition ($M = 31.70$, $SD = 33.49$). However, participants in the cybersickness inducing environment (varying VR) showed a higher (2x2 ANOVA with the factors group and early vs. late heart rate) heart rate across runs compared to the constant VR group ($F(1, 36) = 4.25$, $p = .047$, $\eta_p^2 = .106$), which often is an indicator for cybersickness.[3]

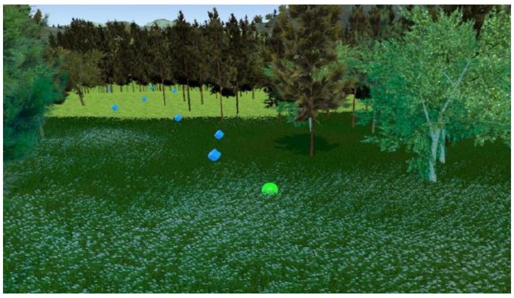

Fig. 1
Neurofeedback paradigm

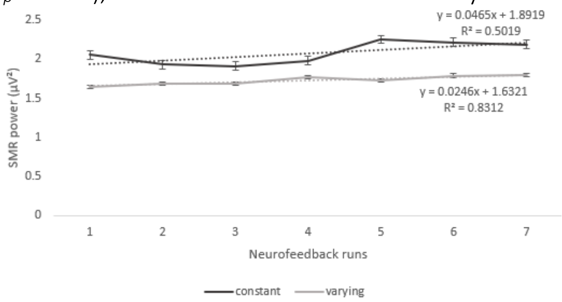

Fig. 2
Mean SMR power during NF training (error bars show SE)

Discussion: Cybersickness did not interfere with the NF success under these specific conditions, even though the cybersickness inducing VR environment (varying VR) resulted in descriptively higher sickness symptoms compared to the constant VR environment.
Significance: Showing that sickness symptoms in VR do not necessarily impair NF/BCI training success takes us one step further in evaluating the practicability of VR in BCI and NF applications.

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Pseudo Online Framework

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Introduction: A BCI technology can operate in 3 different modalities: *online* mode which requires analyzing the new real-time EEG data while acquiring it, *offline* mode where data is acquired and saved to a file and then analyzed afterwards (giving access to the data as a whole) and *pseudo-online* mode, which is a mix between the previous two modes, where stored acquired data is processed as if in *online* mode, but with the relaxation of the real time constraint. Currently, many studies concerning Brain Computer Interfaces (BCI) are tested in the *offline* mode. This thus leads to unrealistic performance compared to real-life online scenarios [1]. The MOABB [2] framework typically provides tools to evaluate algorithms in this *offline* mode. Other studies propose *online* algorithms evaluation, but often do not disclose the datasets and/or nor the code used for data analysis. There are other frameworks for *online* processing [3, 4], but they do not focus on the statistical evaluation over several sessions/subjects as MOABB does.
Material, Methods and Results: The objective of this research is to extend the current MOABB framework, which is currently limited to *offline* mode to allow comparison of different algorithms in a *pseudo-online* setting. We focus on asynchronous BCI where data is typically analyzed in overlapping sliding windows. This requires the addition of an *idle* state event to the datasets to mark signal pieces not related to an actual BCI task(s). Doing so generates datasets that are usually highly unbalanced in favor of this *idle* event, generating problems with some of the standard metrics used in BCI evaluation. We thus use the normalized Matthews Correlation Coefficient (nMCC) [5] and the Information Transfer Rate (ITR) [6]. We applied this pseudo-online framework to evaluate the state-of-the-art algorithms over the last 15 years over several Motor Imagery (MI) datasets composed by several subjects.
Discussion: Usually *offline* modality set an upper bound to the performances, while a *online* signal analysis approaches generally produce results that are less accurate but more representative of a therapeutic application usage [7]. The *pseudo-online* implementation can be used as a methodology that best approximates the *online* process while still processing the data after complete recording. It still represents an upper bound on performance (as real time time is not required) but a more realistic one that can be reached with more powerful computing resources.
Significance: The possibility of analyzing the performance of different algorithms first *offline*, followed by subsequent validation of performance in *pseudo-online* mode, will be enable more representative reports on the performance of classification algorithms for the BCI community.
Acknowledgements: This work has been partially financed by a EUR DS4H/Neuromod fellowship. The authors are grateful to the OPAL infrastructure from Université Côte d'Azur for providing resources and support.

Keywords BCI-EEG, Asynchronous BCI, MOABB, Pseudo Online BCI, Deep Learning, Machine Learning.

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Detecting Focus States in Office Environment with Neurable EEG Headset

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Introduction: Workers switch between different states of focus throughout the day, such as deep focus, productive multitasking, and unproductive multitasking [1]. Recently, Neurable designed a machine learning algorithm to estimate a focus score metric from the normalized alpha band extracted from EEG signals [2]. We expanded this work to explore changes in alpha power, as shown by the focus score, with the intention of classifying when a distraction is work related, as it is in productive multitasking, such as looking between notes and work, and not related to work, as it is in unproductive multitasking, such as emails unrelated to the current task.

Material, Methods, and Results:
We developed an algorithm to predict the focus state a user is in using Neurable's headset [2]. We collected 114 hours of EEG data from 43 participants who were engaged in their daily work activities in an office environment. We labeled each dataset as deep focus (DF), productive multitasking (PMT), or unproductive multitasking (UMT) based upon user reflections. Participants recounted their work session, including times when they switched tasks or multitasked, and often acknowledged that drops in their focus score correlated to times when messages or emails were received. Our ground truth datasets were when the participant stayed within a single focus state (70 hours) to train a model that predicted the focus state (DF, PMT or UMT), and tested it on datasets where participants indicated they had switched focus states (24 hours), with 20 hours of data removed due to noise artifacts. Our model correctly identified when users switched focus states in 83% of the datasets (Fig. 1).

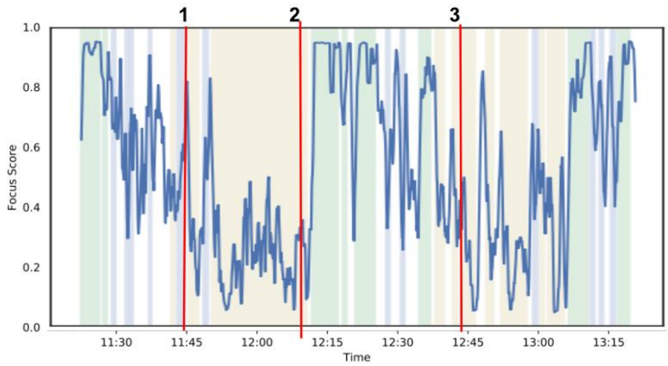

Figure 1. The user was in DF (green) and PMT (blue) while writing a grant, then would shift to UMT (yellow) as they started to respond to unrelated emails (Line 1). After finishing the unrelated work and sending a draft of the grant to a colleague, the user switched back to DF as they focused on only grant writing again (Line 2). Finally, they went back to UMT as more unrelated emails came through that they needed to respond to (Line 3).

Discussion: In this study, we showed that different states of focus can be accurately tracked with Neurable EEG headset and algorithms. This enables the development of EEG products that can help users track their attention and potentially limit factors that lead to unproductive multitasking.

Significance: We've shown the ability of a consumer grade BCI to detect changes in workers' focus state in an office environment. This takes a large step towards incorporating BCIs in daily work activities, similar to how movement and heart rate trackers have become integrated into daily life.

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TSMNet for BCI: online, unsupervised adaptation

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Introduction: Besides generalization across days (=sessions) and subjects, brain-computer interfaces (BCIs) for healthcare require a high degree of interpretability while being robust to scarce data. Recent works [1-3] indicate that geometric deep learning, combing deep learning with Riemannian geometry, has the potential to meet this demand for EEG-based BCI systems. In [1], we proposed a geometric deep learning framework to learn typical tangent space mapping (TSM) models [4] end-to-end. With an intrinsically interpretable neural network architecture, denoted TSMNet, we obtained state-of-the-art performance in EEG-based BCI inter-session and -subject unsupervised domain adaptation (UDA) problems. Here, we propose an unsupervised adaptation scheme to extend our framework to data stream settings (i.e., online BCI).

Methods and Results: TSMNet [1] relies on domain-specific batch normalization (DSBN) on the symmetric positive definite (SPD) manifold to align the first and second order moments across domains in latent space. To extend DSBN on the SPD manifold to a data stream setting, we evaluate several initialization and online algorithms to estimate the Fréchet mean and variance of unseen domains. Using BCI competition dataset 4a, we found (Figure 1) that (1) the initialization and adaptation methods quickly converge to the performance of the oracle (=TSMNet with UDA on entire target domain data), (2) the previous session's mean and variance drastically improve initial performance upon standard normal (identify matrix and unit variance) initializations, and (3) in inter-subject transfer, finetuning the classification layer to session 1 of the target subject performs as well as inter-session transfer.

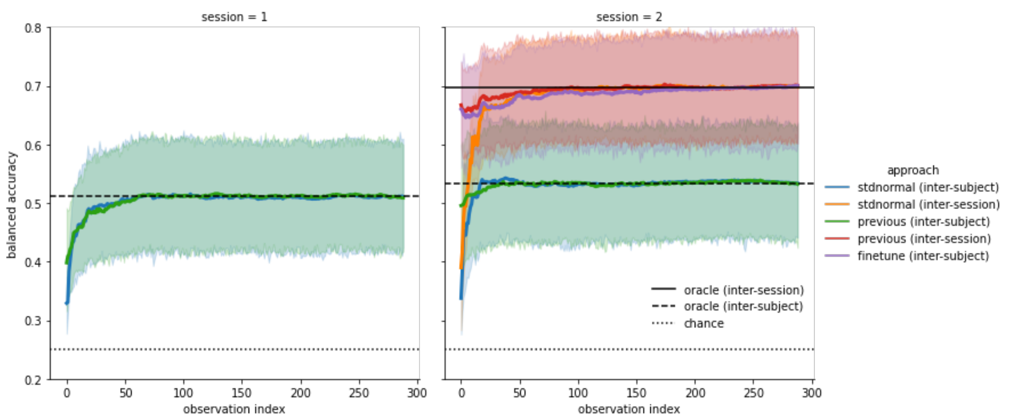

Figure 1. Session 1(left panel) and 2 (right panel) test set performance (balance accuracy score) over the observations index (1 to 288) as a function of the considered initialization schemes and unsupervised transfer learning settings (inter-session and -subject).

Discussion and Significance: Our simulation results with a single dataset suggest that TSMNet can be readily adapted to unseen sessions and subjects without retraining the entire model.

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The whole-cortical ECoG reveals association cortices contribute multimodal intentional decoding

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Introduction: BCI enable patients with CNS damages, who have difficulties to move their body or to speak, to move prosthetic limbs or to communicate with other people by using their own neural activity. However most of the recent BCIs have been developed for limited tasks. For BCIs to be more widely used, it is important to decode subjects' multimodal intentions from a limited number of recording electrodes. It is little known whether there are common brain areas which highly contribute to both action and vocalization. To answer this questions, we investigated which cortical areas are suitable for multimodal decoding by a data driven manner.

Material, Methods and Results: Two common marmosets, small non-human primates, are implanted with the whole-cortical ECoG array [1], which allow us to monitor whole-cortical neural activity. We conducted wireless ECoG recordings from these animals under a free-moving condition. Then, we annotate action categories and vocalization types based on movie and audio data, which were recorded simultaneously with the ECoG signals. Then, we developed a decoder to predict multi-modal features of marmoset behaviors, and quantified spatiotemporal contributions of the whole-cortical ECoG. We found that the frontal, temporal, and parietal association cortices showed a large contribution to the decoding of both action and vocalization types.

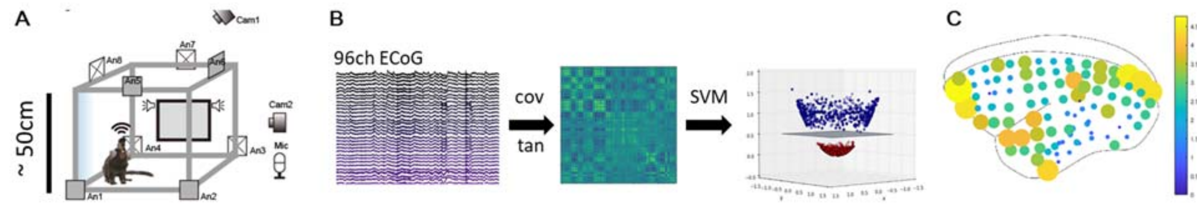

Figure 1. *A) Experimental setup for wireless ECoG recording system with a free-moving marmoset. B) Decoder construction. C) Spatial map of contribution for multi-modal decoding.*

Discussion & Significance: We decoded multi-modal features of marmoset behavior from whole-cortical ECoG, and quantified spatiotemporal contributions. The results demonstrated that association cortices contribute multimodal intentional decoding, such as actions and vocal productions. This findings may paves a new way for multimodal BCI with much higher degree-of-freedom.

Acknowledgements: This study was supported by JST, Moonshot R&D, Grant Number JPMJMS2012.

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Detecting bluffing in a two-player game with passive brain-computer interfaces: implications for human-machine interaction

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Introduction: Machines are becoming a ubiquitous presence in human day-to-day life and autonomous systems are increasingly making decisions for us. Nevertheless, our interaction with these systems feels incomplete as the implicit and non-verbal cues that are crucial in human communication are overlooked [1]. A solution to this problem could be brought by passive brain-computer interfaces (pBCIs), which have proven valuable in decoding cognitive and affective states from brain activity [2]. With this study, we show that pBCIs are able to distinguish truths from bluffs more accurately than human participants. Our findings provide deeper understanding of the significance and potential contributions of pBCIs in contexts that involve social interaction.

Material, Methods and Results: The study included 6 pairs of participants that played 8 rounds of a dice game that involves both bluffing and truth-telling, illustrated in *Figure 1*.

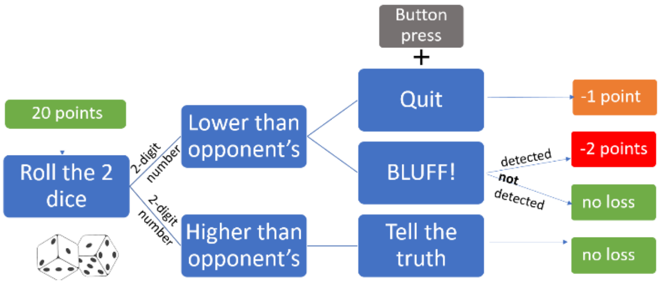

Figure 1.Scheme of the bluffing game's rules

All players' brain activity was recorded with 128 EEG electrodes. Final game points were converted into monetary rewards. Hence, players were motivated to bluff and detect the opponents' bluffs. To contrast bluffs versus truths, we extracted samples of data time-locked to the button presses that preceded each player's announcement of either the true number on their dice, or their bluffs. We excluded quitting trials. The pre-processing and feature extraction method followed a windowed means approach [3] and a bandpass filter (0.1 – 8 Hz). For the training and testing classification, we used a regularized linear discriminant analysis (rLDA) and a 5x5 cross-validation method. The pBCI system managed to distinguish truths from bluffs with an accuracy of up to 76%, significantly higher than the overall human opponents' accuracy of 66%.

Discussion: Our classifier accurately distinguished bluffs from truths, showing ability to detect complex mental states from EEG that surpasses a human's ability to do the same based on facial, social, and contextual cues. An analysis into the neural sources that contributed to classification indicates that cortical sources including the anterior cingulate cortex (ACC) play a key role in the deception mechanism, in line with neuroscientific studies on the subject [5].

Significance: Despite the lack of access to hidden states, recent advancements show AIs can beat humans at poker [5], demonstrating that some AIs can handle real-world, social scenarios. But what if AI systems would have access to such hidden information? Would a caregiver robot understand its elder patient's needs more and empathize better? Or would an AI algorithm be able to contribute to difficult negotiation sessions? Although we cannot answer these questions, this study lays the foundation for understanding how to improve human-machine relationships with pBCI.

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Design and Evaluation of Vibrotactile Stimulus to Support a KMI-based Neurofeedback

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Introduction: We are developing a brain-computer interface integrating visual and vibrotactile feedback on the forearm and the hand in a gamified virtual environment to give situated and embodied information about the quality of stroke patients' kinesthetic motor imagery (KMI) of a grasping movement. Multimodal sensory stimuli are used to provide a sense of embodiment [1]. Particularly, adding vibrotactile feedback is expected to improve the performance of a motor imagery task in neurotypical [2], [3], and stroke participants [4].

Material, Methods, and Results: Three vibration motors are activated using triggers sent by an OpenViBE scenario via an Arduino Nano (Figure 1). They are synchronized with our existing BCI Grasp'it [5]. Our conception process consists of 3 stages: 1) designing the vibrotactile feedback by first establishing the minimum and maximum vibration intensities for three groups of participants based on their ages (18-39, 40-59, 60≤). Then, we compared a sequential vs. a simultaneous activation pattern using 2 vs. 3 motors. Participants seemed to accept either configuration as a support to the visual animation of a hand grasping a bottle. 2) Validating the BCI with a neurotypical population by comparing visual, vibrotactile, and bimodal (vibrotactile + visual) feedback conditions to identify the one preferred by users and that helps the most to perform KMI. Preliminary results indicate that 72% of participants preferred bimodal feedback and they considered performing better under this condition. For the last stage 3), we will evaluate the multimodal BCI in terms of performance, usability, and attractivity with post-stroke patients and therapists.

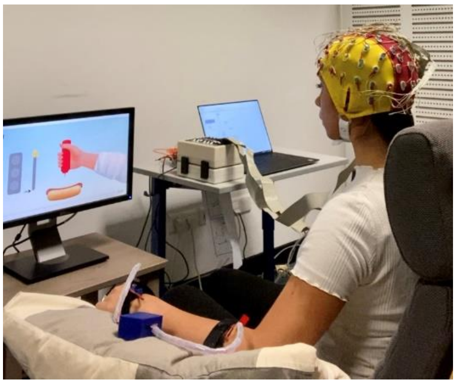

Figure 1. *Three vibrotactile motors are located on the hand and the forearm. Their activation rotation frequencies and duration are synchronized and analogous to the visual feedback corresponding to four different levels of a grasping movement.*

Discussion: The acceptance of both vibration activation patterns may be because they were congruent and synchronized with the visual stimulus. The vibration may help execute the KMI task by delivering skin stimulations above targeted muscles.

Significance: Vibrotactile feedback can help a large majority of BCI users to perform a KMI task by offering complementary information to the user and a better overall experience.

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Do nature documentaries affect event-related desynchronization (ERD) induced by motor imagery neurofeedback?

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Introduction: Motor imagery (MI) in combination with neurofeedback (NF) has gained interest in several research areas, including motor neurorehabilitation. It is well known that MI practice affects performance and motor learning. Yet, how the context in which MI-NF training takes place affects event-related desynchronization (ERD) as a commonly used NF modality is scarcely explored. Daeglau and colleagues postulated that the contextual factor of declarative interference following MI-NF has a negative effect on the development of ERD [1]. However, no change in ERD within the mu and beta (8-30 Hz) frequency range was observed across sessions in either the experimental or control conditions. This study investigated whether these unexpected results could be attributed to the use of nature documentaries as a pause and control task. Therefore, in an additional control condition, nature documentaries were replaced by quiet rest. ERD results were compared with the no-interference control group of [1].

Material, Methods, and Results: 64-channel EEG data were recorded from 17 healthy subjects (8 females, 18-35 years, M and SD: 25.2 ± 4.2 years) who completed three sessions of kinesthetic MI-NF of a simple finger-tapping task (FTT) on two consecutive days (*group quiet rest*). Results were compared to the no-interference group (17 participants, 10 females, 23-32 years, M and SD: 25.8 ± 2.5 years) of [1] (*group documentaries*). Descriptively, no increase in MI NF ERD was observed over sessions (Figure 1). This was confirmed with a mixed repeated measures ANOVA. Neither session ($F_{(2,64)} = 1.831$, $p = .169$, $\eta^2 = .01$) nor group ($F_{(1,32)} = .055$, $p = 0.815$, $\eta^2 = .001$) showed a significant main effect. A significant interaction effect (session*group) was present ($F_{(2,64)} = 3.526$, $p = .035$, $\eta^2 = .019$) but subsequent paired t-tests showed no significant difference in conditions ($p_{bon\text{-}holm} \geq .144$).

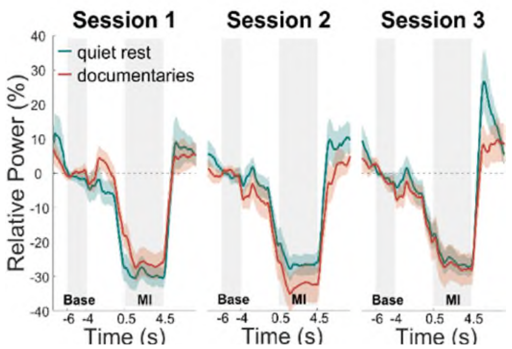

Figure 1: *Time courses of MI NF ERD of group quiet rest (blue) and documentaries (red).*

Discussion: If nature documentaries prevent or reduce across-session ERD gain, this should have become apparent in the comparison of data sets. However, ERD was highly comparable between groups. Similarly structured MI-NF studies have demonstrated an increase in ERD over multiple sessions [2, 3]. Whereas the contralateral ERD did not change across sessions in Zich and colleagues, the ipsilateral ERD did decrease, indicating an ipsilateral learning effect, which was not examined in the present study [2]. Ono and colleagues have shown that different types of NF led to enhanced ERD, while realistic congruent NF is more effective than 2D object-based NF (similar to ball steering used as NF condition here) [3]. Additionally, the simplicity of the FTT should be considered, as more complex practice structures can have a beneficial effect on MI [4].

Significance: MI with NF is a promising approach in neurorehabilitation, although a non-negligible number of users do not exhibit adequate NF performance. Contextual factors might contribute to this. Here, resting and watching a nature documentary had similar effects on the MI-NF induced ERD, indicating no general contextual influences from the documentary. However, contextual factors might further exacerbate interindividual differences [4]. Future research should continue exploring the effect of context factors relevant for observing an ERD gain across MI-NF sessions and the functional significance of its presence/absence.

Acknowledgements: We acknowledge the contributions of S.K. Saak, J.F. Scheffels and J. Welzel to study design and data collection in group documentaries.

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Neural tracking of acoustic onsets: Towards understanding the brain beyond the lab

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Introduction: We are interested in the neural dynamics of sound processing in everyday life. One challenge in the interpretation of EEG in response to everyday sounds is the extraction of optimal auditory features that are 1) easily obtainable from the environment in everyday situations and 2) provide sufficient information to gain insights into the brain response. In this study, we compare different sound features and evaluate them in their potential for beyond the lab recordings.

Method: We re-analyzed an existing dataset where participants performed an audio-visual-motor 3D Tetris task while listening to a realistic soundscape of a surgery room [1]. We extracted a multitude of low-level acoustic features (i.e. envelope, acoustic onsets) and used temporal response functions (TRF) to predict the EEG response. The performance of the derived neural model was compared to a held-out testing set. Using variance partitioning, model prediction was compared by determining the shared and unique variance of each feature of interest. Additionally, we compared experimentally relevant sound markers to unlabeled acoustic onsets, as this additional marker information is not readily available for beyond the lab recordings. At last, we use event density estimation of the soundscape to derive neural models representing periods of high and low acoustic event density, investigating real-world acoustic dynamics.

Results: The results show that automatically detected onsets from continuous sound streams can be used to derive plausible neural models, that in terms of model, predictions are comparable to validated features, such as the envelope. We find that model prediction with reduced data availability improves when more information about the acoustic stimulus is present (i.e. experimental marked sound type vs. onset only). At last, we show that during periods of high acoustic event density compared to low event density, a reduction in the neural response can be observed.

Discussion: We demonstrate that detected onsets based on acoustic transients are sufficient to monitor sound processing in daily life when using EEG beyond the lab. Our results will help to understand neural changes in response to changes in the environment.

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DUPE MIBCI: Database with User's Profile and EEG signals for Motor Imagery Brain Computer Interface research

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Introduction: The strong observed variations in BCI performance between participants remain a critical BCI topic that is yet to be fully understood and addressed [1]. To do so, BCI research transparency and efficiency needs to be supported by open access databases of electroencephalographic (EEG) signals collected during BCI training experiments. Also, the inclusion of detailed BCI users' profile data in a large public database is regrettably scarce in the field. Therefore, we shared a large database as the result of several experiments conducted using the same Motor Imagery (MI) BCI protocol, that we present below.

Material, Methods and Results: Our database contains EEG signals from 87 participants. It also contains the participant's online performances, responses to 6 questionnaires related to demographic information, spatial abilities, pre- and post-experiment user states (e.g. fatigue, mood, motivation), learning style [2] and personality and cognitive profile [3]. We provide information on the study design and instructions, methods, and codes used to conduct the studies (scenarios and scripts used to run the experiments with the free and open-source BCI platform OpenViBE [4]). To ensure data quality and/or transparency, the raw signals were all replayed and double-checked by an experimenter. In addition, we computed topographic event-related spectral perturbation (ERSP) between 8-30 Hz for each subject and phase, to check for possible unusual ERD/ERS patterns. It enabled us to visualize possible problems in some EEG signals and annotate the data accordingly.

Discussion: Such database could prove useful for various studies, including but not limited to: 1) studying the relationships between BCI users' profiles and their BCI performances, 2) studying how EEG signals properties varies for different users' profiles and MI tasks, 3) using the large number of participants to design cross-user BCI machine learning algorithms or 4) incorporating users' profile information into the design of EEG signal classification algorithms. In addition, a branch of BCI and EEG research is dedicated to designing signal processing algorithms to detect, reject or clean noise in EEG signals [5] or to designing machine learning algorithms robust to such noise.
Database available at: https://doi.org/10.5281/zenodo.7554429

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How different immersive environments affect intracortical brain computer interfaces

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Introduction: Current methods for controlling a virtual or robotic limb using a brain computer interface (BCI) often involve decoding motor intent from primary motor cortex (M1) while a subject is working in a virtual environment. These virtual workspaces can differ in how immersed an individual feels while completing tasks and interacting with objects in that environment, yet more work is necessary to understand how varying the immersive properties of an environment impact overall BCI control [1].

Material, Methods and Results: We asked human participants implanted with intracortical multi-electrode arrays in M1 to perform a basic 3D grasp and carry motor imagery task in two different environments. In one setting, subjects wore a virtual reality (VR) headset allowing for complete immersion in the virtual environment. In the other setting the same task scene was presented; however, subjects interacted with this virtual environment by looking at a fixed view on a TV screen. We found that overall performance on the task was significantly better in the VR environment in participant C1 (73% vs. 62% success) with path lengths about half as long and faster movements during the carry phase (2.4 s vs. 4.0 s, $p<0.001$, Wilcoxon rank sum test), while participant P2 performed about equally in the two environments. We then trained separate offline linear decoders for each environment to decode hand velocity from neural activity and evaluated model performance using the fraction of variance explained (R^2) within and across environments. We found that R^2 values were similar for all conditions (Table 1).

train set / test set	**TV / TV**	**VR / VR**	**TV / VR**	**VR / TV**
Session 317	0.32	0.26	0.24	0.27
Session 331	0.18	0.08	0.21	0.19
Session 333	0.26	0.26	0.24	0.28

Table 1. *R^2 values for offline linear decoders trained to decode hand velocity in one environment and tested in the same or other environment (denoted as test / train in column headings) across three different experimental sessions for participant C1. Note the similarity in R^2 values across environments.*

Discussion: These results suggest that neural activity is similar across environmental setups despite any differences in immersion quality. While more immersive workspaces may provide better online performance metrics and be preferable as noted by participant C1, neural activity appears to be generalizable across environments.

Significance: Given the expanding future of BCIs and integration with VR technology, it is important to continue examining differences related to the types of environments in which BCIs are used as this will help develop better assistive devices and overall BCI control. Further, these results provide preliminary evidence that BCI control may generalize between 2D and immersive 3D environments.

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Decoding hand kinematics from brain-wide distributed neural recordings

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Introduction: Recent studies suggest that the cortical homunculus is ready for an update.[1] It seems as though several body integration centers exist within the motor cortex that receive input from areas distributed throughout the brain.[1] These integration centers contain highly decodable information[2], raising the question whether the areas that provide input to these centers contain similarly decodable information. In previous work, we started to explore whether it is possible to decode movement-related information from distributed recordings[3] and show that this is indeed possible for both executed and imagined movements. Here, we extend this work from a trial-based classification problem to continuous decoding of hand kinematics using depth electrodes implanted throughout the brain.

Materials, Methods and Results: We developed a continuous movement task in which the participant had to move their hand to target locations in a 3D space using an UltraLeap motion tracker. The targets were displayed on a screen, where the size of the cursor determined the depth axis (towards and away from the screen). We included multiple participants implanted with multiple depth electrodes for their epilepsy clinical treatment. We recorded as much data as possible per patient over multiple sessions, depending on available time, skill and participant well-being (minimum of 25 targets). After preprocessing, we trained and reconstructed hand kinematics using the preferential subspace identification algorithm[4], and reached reconstruction correlations significantly above chance.

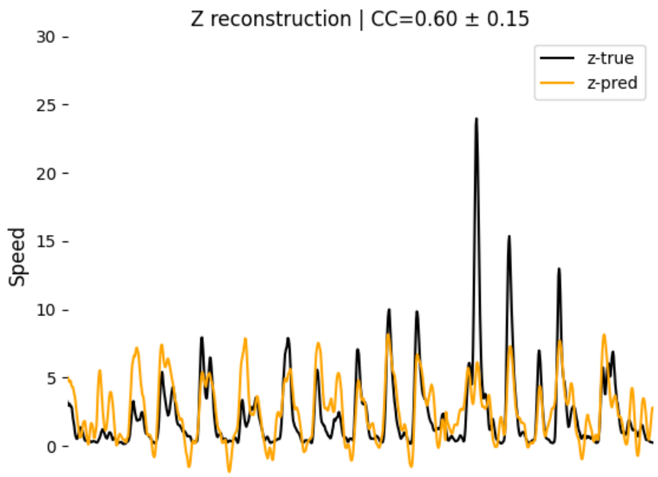

Figure 1. Example speed reconstruction of one participant.

Discussion: These preliminary results suggest that continuous decoding of hand kinematics is possible from distributed recordings. Variations in decoding performance indicate that some areas contain more information relevant to continuous hand movements compared with other regions. However, even for some participants where correlations between the neural signal and hand trajectory were low, the decoder was able to achieve significantly above chance performance.

Significance: The results may identify new brain areas that contain movement-related information, as well as uncover decodable distributed motor-related networks.

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Online Information-Based Stimulus Optimization for P300-based Brain-Computer Interfaces

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Introduction: Brain-computer interfaces (BCIs) interpret users' intent by extracting relevant information from their brain signals. Visual P300-based BCIs [1] enable users to select a target object on a screen by interpreting their responses to a series of stimuli. The BCIs operate by identifying event-related potentials (ERPs) elicited in response to presentations of the user's target object. As ERPs are embedded within noisy brain signal data, the user's target object must typically be presented several times to be identified with confidence. Conventionally, stimulus presentation schedules are designed pseudo-randomly [1, 2]. BCI communication rates may be improved by leveraging real-time user data to adapt stimulus schedules [3, 4, 5]. We previously proposed an information-based algorithm for adaptive BCI stimulus selection that optimizes the prior probability mass of a hypothetical future stimulus [5]. Here, we present results from an online study of our proposed adaptive diffuse stimulus presentation paradigm, which uses our previous algorithm to dynamically select stimuli in real-time and mitigates adjacency distractions in a matrix BCI layout by designing stimuli with non-adjacent components.

Material, Methods and Results: We recruited 21 participants from the Duke University community for an online study comparing our adaptive diffuse paradigm and the pseudo-random checkerboard paradigm [2]. Each participant spelled 30 characters to train a user-specific classifier and spelled 30 characters using the trained classifier during online BCI operation.

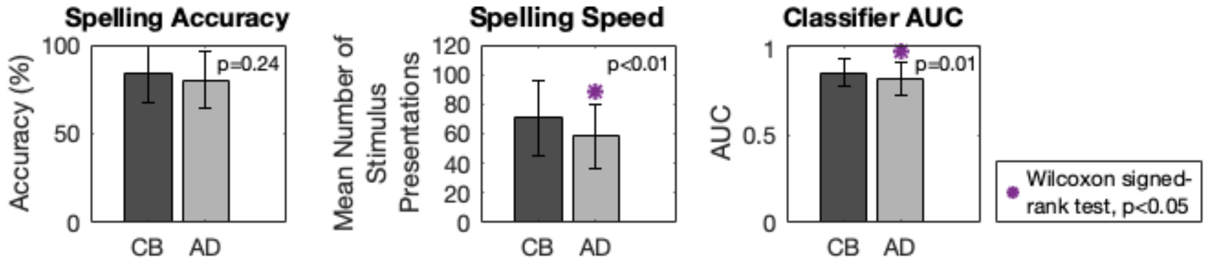

Figure 1. Mean participant performance (N=21) with the checkerboard (CB) and adaptive diffuse (AD) paradigms. AUC: Area under the receiver operating characteristic curve.

Discussion: We demonstrated statistically significant improvement in online spelling speeds with our adaptive diffuse paradigm (Fig. 1), compared to the checkerboard paradigm. However, there were slight decreases in spelling accuracy and classifier performance with the adaptive diffuse paradigm. Post-hoc analysis suggested that this arose due to refractory effects from low intervals between presentations of the target character, which can likely be mitigated by imposing a higher minimum interval between presentations of the same character.

Significance: We present a novel adaptive stimulus selection paradigm for the P300 speller that optimizes stimuli in real-time and improves spelling speeds relative to a conventional paradigm.

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Actively Multiplexed µECoG Array Based on Thin-Film Electronics for High-Resolution Brain Mapping

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Introduction: Electrode arrays are used in neuroscience research and the clinic to record electrical activity from the surface of the brain. However, current passive electrocorticography (ECoG) technologies have low spatial resolution and/or limited cortex coverage. The electrode-count and density are restricted by the fact that each electrode must be individually wired. Here, we present an active µECoG that circumvents these challenges while achieving significantly lower noise compared to other existing active µECoG arrays.

Material, Methods and Results: The proposed neural interface consists of a flexible, actively-multiplexed 256-electrode array and an incremental-ΔΣ readout integrated circuit (ROIC) [1, 2]. The 1×1-cm^2 µECoG array is based on a metaloxide thin-film transistor technology on a 15-µm flexible foil, Fig.1(a), and is coupled to a 1.25×1.25-mm^2 CMOS ROIC fabricated in a 22-nm FDSOI process. Thanks to the 256:16 time-division multiplexing achieved in the electrode array, only 16 multiplexed channels are required to acquire signals from all the 256 electrodes simultaneously. The proposed system has been validated in-vivo by recording spontaneous activity and somatosensory-evoked potentials in anesthetized mice, Fig.1(b).

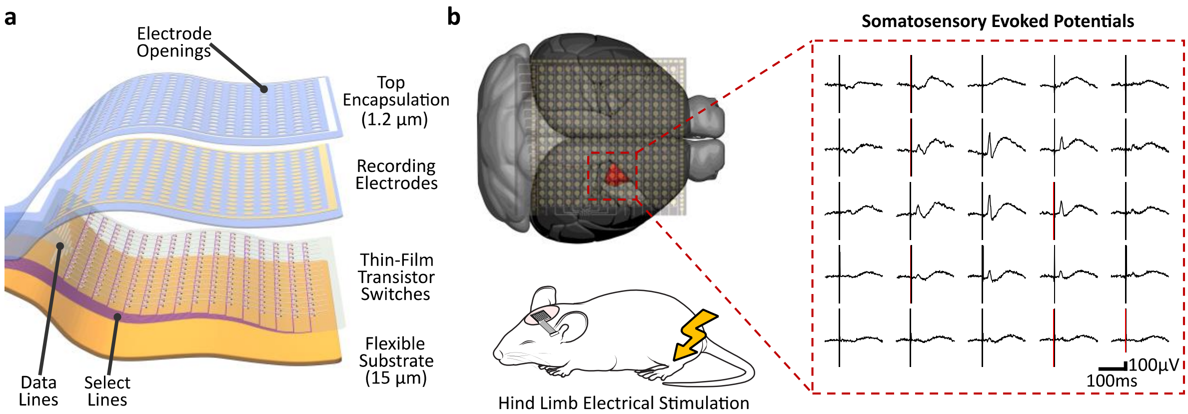

Figure 1. *Actively multiplexed µECoG array based on metaloxide thin-film transistors. a) Exploded-view illustration of the 256-electrode array, b) in vivo validation by recording somatosensory-evoked potentials.*

Discussion: By combining TFT multiplexing with newly proposed bulk-DAC feedback in the readout channel, we can integrate and address more electrodes than other passive arrays, achieve >10x less noise than existing active arrays, and obtain >2x effective channel area reduction in the ROIC, while maintaining comparable electrical performance over state-of-the-art ECoG readouts.

Significance: Our neuroelectronic interface platform overcomes the wiring bottle neck that limits many neural acquisition systems and has application potential as a tool for better mapping the cerebral cortex or as an enabling technology of future brain-machine interfaces.

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EEG potentials evoked by deep brain stimulation in patients with treatment-resistant depression

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Introduction: There is growing pre-clinical and clinical evidence supporting deep brain stimulation (DBS) of the superolateral medial forebrain bundle (slMFB) as a therapeutic option for neuropsychiatric disorders like major depression disorder and obsessive-compulsive disorder [1,2,3]. Typical stimulation occurs in the ventral mesencephalic tegmentum. Despite its benefits, the electrophysiological effects of slMFB-DBS in the human brain remain to be characterized. Unravelling the *optimal* patient-specific stimulation parameters is a challenging task, and characterizing slMFB-DBS effects on cortical regions and networks could contribute to the optimization of stimulation patterns in the future. This work presents the protocol to study EEG responses evoked by single slMFB-DBS pulses and first results on two patients suffering from treatment-resistant depression with bilateral implants in the slMFB.

Methods and Results: Therapeutic (130 Hz) DBS was discontinued at the beginning of the session. Patients were instructed to fixate their gaze on a cross and remain at rest during 2-min blocks. Several blocks were recorded during which different, patient-dependent, DBS stimulation conditions were applied. DBS was delivered in a 2Hz frequency. DBS-evoked responses were obtained by averaging the pre-processed and cleaned EEG signals (128-channel setup) time-locked to the stimulation artefact (per block, around 240 trials were obtained). Averaging was done separately per DBS condition (Fig.1 corresponds to the results of a single block for one participant). EEG source imaging was used to estimate the sources of specific DBS-evoked components, using patient-specific head models. These are interpreted in the light of patient-specific patterns of structural connectivity, and additionally on the patient-specific clinically relevant responses to DBS.

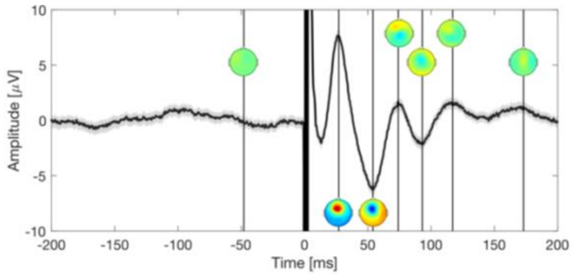

Figure 1. *DBS-evoked cortical potential on channel FFC1 (t = 0 corresponds to stimulation artefact).*

Discussion: We show for the first time that DBS-evoked potentials can be observed as a response to single pulses of stimulation in the slMFB in patients with depression. Throughout the runtime of this study, with patient recruitment still ongoing, the test-retest reliability of the evoked-responses and their modulation based on different stimulation parameters will continue to be evaluated.

Significance: In the future, such a fast screening of DBS-evoked cortical potentials could become an objective method to measure the DBS target engagement, and thus guide clinicians in finding optimal stimulation parameters within a short period of time.

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What brain patterns should we reinforce during BCI training procedures targeting motor imagery abilities?

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Introduction: Motor imagery (MI) can be defined as a *"dynamic state during which one simulates an action mentally without any body movement"* [1]. The aim of MI is to optimise learning (e.g., in athletic training) or re-learning (e.g., in motor rehabilitation after stroke) by mastering the technique of new motor skills, but also through attentional focus [2] thanks to brain plasticity mechanisms. Indeed, similarities exist between MI and motor execution with regards to the solicitation of certain brain networks and regions, including premotor, parietal, and somatosensory regions [3]. Current BCI protocols targeting MI consist in positively reinforcing the maximum modulation of sensorimotor rhythms (SMRs) from baseline levels. This suggests that we consider that the growing expertise in the MI task will be associated with a higher desynchronisation of neurons in the sensorimotor cortices [4]. Yet, experiments investigating the neural efficiency hypothesis have shown that experts happen to have a reduced modulation of neural activity in comparison to novices [5], which can be attributed to a more efficient resource distribution. This efficiency would take form of reinforced temporal and spatial stability during MI tasks [6,7]. Thus, our questions are as follows: **Q1.** Does expertise modify the brain patterns associated with a MI task? **Q2.** If so, are those modifications elicited exclusively during MI of mastered movements? Or do these modifications reflect the acquisition of a generic skill (whatever the imagined movement)? **Q3.** Is maximising the percentage of desynchronisation a relevant objective? If not, what metrics of performance should be used in order to optimise the training of users/patients to self-regulate their brain activity?

In order to investigate those different questions, we will recruit athletes who can be considered as an expert population in MI because of their frequent mental training use (to prevent overtraining or during rehabilitation but also as warm-up routines and rehearsal technique).

Material and Methods: We will recruit 48 participants who will be divided into three groups: "basketball experts" (*G1exp*), "dance experts" (*G2exp*) and "novices" (*G3*) [16 participants per group, 8 men, 8 women]. All participants will perform 20 MI trials lasting 10s each for all four of the following movements: a simple reaching action (*T1* – for which all participants are experts), a complex novel drawing task (*T2* – for which none are expert), a basketball free throw (*T3* – expertise of *G1exp* only) and a short pre-defined dancing choreography (*T4* – expertise of *G2exp* only). EEG activity will be recorded during trials. This paradigm will enable us to compare MI-related brain patterns between experts and novices (*G1exp/G2exp* vs. *G3*) **(Q1)**. It will also enable us to assess the extent to which the potential modifications of brain patterns due to expertise are specific to expert movements or generic (for *G1exp* and *G2exp*: *T3* vs. *T4*; for all, control: *T1* vs. *T2*) **(Q2)**. From those results, we will investigate which performance metrics seem the most relevant to use in MI-based BCI/NF paradigms **(Q3)**.

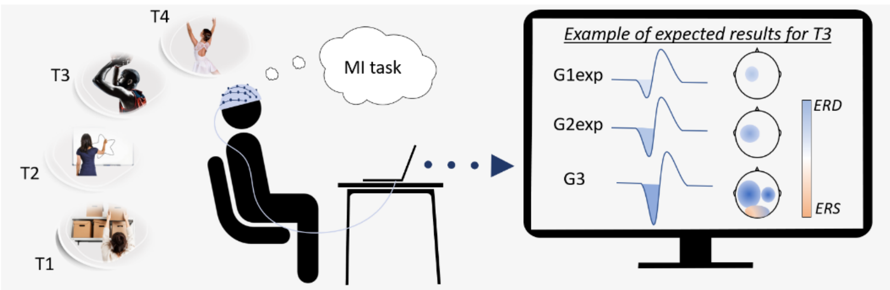

Figure 1. *Experimental procedure that we plan on using*

Discussion: This study will enable us to acquire new knowledge regarding the neural efficiency hypothesis. If our results comfort this hypothesis, it will be important to identify, implement and evaluate new metrics of performance to guide BCI/NF users during their training (i.e., instead of ERD%). Following the neural efficiency hypothesis, we expect experts to show brain patterns that are more spatially and temporally stable than those of novices [6,7]. In other terms, in experts, we expect the modulations of brain activity during MI to be circumscribed to sensorimotor cortices (provided that they perform kinaesthetic MI) and to be highly stable across trials in terms of location and frequency. In addition, we hypothesise that those modulations will represent a general skill. In other terms, we expect the same patterns to be elicited for experts when doing MI of a mastered technique from their discipline, but also when doing MI of a novel movement of similar nature (in our case a different physical activity). Indeed, we believe that a transfer of neural efficiency exists. However, this phenomenon might only happen to a certain extent and not be identifiable for MI of a complex novel task or of a simple everyday life action. To our knowledge, this last hypothesis hasn't been tested in the current literature and will therefore require an exploratory approach.

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Development of an EEG-EMG processing pipeline and Graphical User Interface for analysis, recognition, and peak-negativity detection of movement-related cortical potentials

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Introduction. The rehabilitative Brain Computer Interface (BCI) system looks for restoring brain functions through signal-features that are related to the neurophysiological activity. One critical step in the development of BCI for rehabilitation is feature analysis and selection, because based on these it is possible to detect when the subject's intention occurs, therefore improving rehabilitation success. One of the most known and reliable features is the movement-related cortical potential (MRCP) which reflects voluntary movements, in its stages of preparation or execution. One property of great interest in the MRCP is the peak negativity (PN), the most negative point associated with movement execution. When a subject is performing a cue-based movement, it is possible to observe PN arriving 0.5 milliseconds after or even before the cue. Recognizing this time difference respective to the cue is important, because it makes possible to stimulate the target muscle to induce a systematic relationship between the physiologically generated wave during the intention of the movement, and the sensory signal that arrives in the target muscle [1,2,3]. The aim was to develop a processing pipeline and a Graphical User Interface (GUI) for analyzing electroencephalography (EEG) and electromyography (EMG) data, to extract the MRCP in different trials performed by a subject, identifying the PN and the delay based on a certain onset, to calculate the best time to send the stimulus.

Materials, Methods, and Results. EEG signals from 10 channels (FP1, Fz, FC1, FC2, C3, Cz, C4, CP1, CP2 und Pz) and EMG signal from tibialis anterior muscle were recorded from two healthy volunteers (1 female and 1 male, 25 ± 1 years old) during a simple motor tasks (30 dorsiflexions - DF) guided by a visual ramp-cue. The participant performs the movement when the cue was shown in the screen. Each trial was conformed by three phases; Rest (3-4 s), Focus (1-2 s) and Task-execution (4.1 s). During the Task-execution phase there is a triangle cursor moving, after 2 seconds this cursor indicates the moment when the subject has to perform and hold the dorsiflexion until the Task-execution phase finishes.

The EEG and EMG signals were subsequently analyzed offline with a GUI. The EEG data was bandpass filtered between 0.05 to 3 Hz using a 4th order Butterwortth bandpass filter, then segmented into epochs from 2 s before to 3 s after task onset, next the mean was subtracted, optionally, in channel Cz the Laplacian could be also applied, and finally the PN was localized.

The EMG data was rectified, then high-pass filtered with a 4th order Butterworth at 20 Hz [1] and segmented into epochs from 2 s before to 3 s after task onset.

The PN could be localized manually and automatically. Once it is localized in all the trials the delay is measured based on an onset and finally the average is calculated.

Significance. The goal of the GUI is to online analyze trial-wise, and the whole session, to compute the PN delay so to make possible to identify the optimal time to send a stimulus, so to enhance the BCI-based rehabilitation.

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Automated online optimal features selection for an ECoG-based motor Brain-Computer Interface

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Introduction: Motor Brain-computer interfaces (BCIs) create new communication pathways between the brain and the external effectors for severely motor-impaired subjects. The control of complex effectors such as robotic arm or exoskeleton is generally based on real time decoding of high-resolution neural signal. High dimensionality and noise in the brain signal bring challenges to overcome for an online Brain-Computer Interface, such as the decoding model generalization ability and a high computational load. Identification of sparse decoders may allow addressing this problem. Additionally, online closed loop decoder adaptation (CLDA) is known to be efficient procedure for BCI decoders training, allowing taking into account the neuronal feedback. Integration of feature selection directly to the CLDA is potentially beneficial for the system usability, for the decoding performance improvement, and to decrease the computational load during neuroprosthetics use stage. Here, an approach of automated online training of sparse multilinear decoders embedded to CLDA is proposed.

Materials, methods and Results: Sparsity promoting penalization is a common approach to obtain sparse solution. Generally, BCI features are naturally structured and grouped according to spatial (electrodes), frequencies and temporal dimensions. Group-wise sparsity, i.e. the setting to zero the model coefficients within such a group simultaneously, may be beneficial for reducing the computational time/memory and for data transfer. Here, an algorithm for online closed-loop group-wise sparse multilinear decoders training is proposed. Namely, L_p-Penalized Recursive Exponentially Weighted N way Partial Least Square (PREW-NPLS) was explored for three types of sparsity promoting penalization L_p, p = 0, 0.5, 1. The proposed algorithm is a generalization of conventional Recursive Exponentially Weighted N way Partial Least Square (REW-NPLS) algorithm [1] currently employed in “BCI and tetraplegia” clinical trial (NCT02550522, ClinicalTrials.gov) [2], [3]. The algorithms were tested offline in a pseudo-online manner for features grouped in spatial dimension. Epidural ECoG dataset recorded during long-term BCI experiments of virtual avatar control (left / right hand 3D translation) by a tetraplegic was used for comparison study. Novel PREW-NPLS algorithms highlighted comparable or better decoding performance to conventional REW-NPLS, achieved with sparse models. The proposed algorithms are compatible with real time CLDA. The use of penalization requires tuning of the penalization parameter. To solve the problem, a reinforcement learning procedure is proposed to estimate the penalization parameters integrated to CLDA.

Discussion and perspectives: The presented algorithms have been tested in offline, but implemented to process a data stream as if it would have been online experiment. The most promising one still needs to be integrated to be tested in online experiments with a patient. Having such an algorithm performing with high accuracy would allow to have very lightweight decoding software embedded in a small wearable dedicated electronic device.

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Contrastive Self-Supervised Learning for Motor Imagery: impact of the embedding size

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Introduction: Due to the intra- and inter-individual variability of the electroencephalography (EEG) signals, brain-computer interfaces (BCI) require a daily user-specific calibration. This offline calibration step is necessary to set feature extraction, classification and pre-processing parameters. Yet, it is time consuming and might cause fatigue before the actual use of the BCI. Our goal is to reduce this time with a self-supervised classification method that achieves good detections with minimal calibration trials, for use in a motor imagery (MI)-based BCI that aims to enhance the rehabilitation of stroke patients. To process a small amount of labeled data, self-supervised learning (SSL) is currently the state-of-the-art method in the fields of vision and natural language processing [1], which makes it interesting to explore for EEG data.

Material, Methods and Results: Dataset 2a of the BCI competition IV [2] was used to estimate the capability of contrastive SSL (CSSL). Two sessions of 72 trials each are available for training and testing. The classifier has to detect a right (or left) hand MI relative to a resting period. CSSL uses a pretext task (PT) to create sample pairs from unlabeled EEG segments that are similar (close) or dissimilar (far) in time. It projects them in an embedding space accordingly, then reuses it to solve the real task. Our PT is based on Relative Positioning (RP) [3]. For T trials, it produces 2T pairs of similar EEG windows if they belong to the same segment, and 4T(2T-1) pairs of dissimilar ones if they come from different segments. Segments are related to resting or MI periods. The feature extractor is EEGNet [4] without its classification layer, and both pretext and real task classifiers are logistic regressions. Fig. 1 presents the accuracy of the CSSL models among different percentages of the training set, as the number of features extracted, i.e., the size *d* of the embedding space, varies. The process was cross-validated with 6-folds, and averaged across 10 repetitions (except for 100% of training data). CSSL is compared to LDA+CSP with 4 filters, which is better than 6.

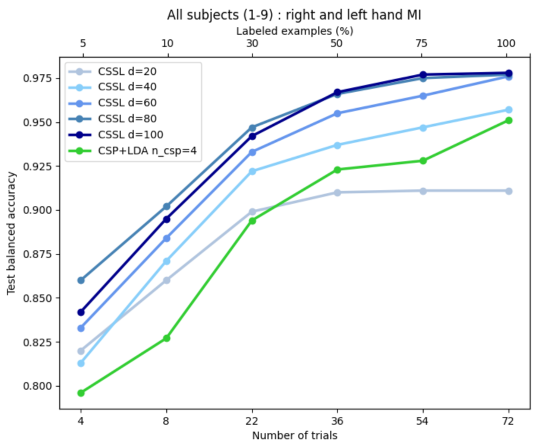

Figure 1. *Test accuracy, averaged across all subjects, for the detections of MI vs rest (BCI IV Competition dataset 2a), obtained by SSL models, as a function of the percentage of labeled training data. The embedding size is noted as* d.

Discussion and Significance: As *d* increases, the accuracy of CSSL models improves, from an accuracy above 80% when trained with only 4 trials, to nearly 98% with more than 54 trials. In particular, the accuracy for d=80 is better than for d=100 with smaller datasets, meaning that the performance saturates as the amount of features extracted increases. A Student test ($p < 0.05$) with a Šidák correction for 6 methods considers the different models almost two by two statistically equal due to the small sample size. Nevertheless, CSSL shows higher accuracies and confirms its capability to extract useful features from unlabeled data.

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Towards including covariates in EEG classification - a preliminary study on simulated data

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Introduction: The classification models commonly used in BCIs do not take into account covariates such as changes in users' mental states, such as motivation or fatigue, which can influence EEG signal dynamic [1] and affect classification performances. We propose a modification of linear discriminant analysis (LDA) [2] to account for these interfering covariates in order to improve performance. Our modification aims to make the LDA linear projection independent of such covariates for improved performance.

Material, Methods and Results: LDA aims to reduce the dimension of the input variables while separating them into classes using a linear combination of the input variables. To do so, it computes the input variable means and covariance matrices for each class. They are used to determine the linear projection that maximizes the distance between class means and minimizes variance within each class. Our method, named independant LDA (iLDA), takes as input a vector of x_i, which is an original variable x to which we subtracted the linear influence that the covariate z has on x, using linear regression (here we used the mean square error regression method), see equation 1. This allows us to clearly consider that the covariate has an influence on the variable and to reduce such influence by projection.

$$x_i = x - (a \ * \ z + b) \tag{1}$$

Equation 1 . x is the original input variable, x_i is the variable were the linear influence of the covariate was removed, a and b are the regression coefficients and error term of the linear regression predicting x from z, z is the covariate

The algorithm was tested on simulated data where each variable follows a normal distribution, with different distributions for each class. A randomly chosen covariate, with a linear influence on all variables, was generated, and a small Gaussian noise added to the covariate. The data have been generated for a different set of variables, from 2 to 100, and a different number of training instances, from 25 to 1000. Each set of condition is repeated 1000 times. The simulated data was tested with three classifiers: a standard LDA, an LDA with the covariate added as input variable (covLDA), and our proposed iLDA. Results showed that both LDAs including the covariate (i.e., covLDA and iLDA) improved classification accuracy (respectively 92.1% and 92.5%) compared to standard LDA (91.3%) and that our model performed significantly better than covLDA in cases with few training instances and many variables.

Discussion: These preliminary results on simulated data showed the interest of considering covariates in classifiers. Our next steps is to test such algorithms with real EEG datasets and features (e.g., band power or CSP features), and covariates that are known to have an influence on EEG signals such as fatigue, attention, motivation, expertise or artifacts, as measured using, e.g., questionnaires.

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Electrovascular Phase-Amplitude Coupling During an Auditory Task

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Introduction: Although noninvasive multimodal neuroimaging approaches relying on electroencephalography (EEG) and functional near-infrared spectroscopy (fNIRS) have shown great promise in open and closed-loop brain-computer interface (BCI) applications, the underlying neural dynamics relating these neuroimaging modalities are not well understood. In this pilot study, we explore phase-amplitude coupling (PAC) between the low-frequency oxygenated hemoglobin concentration change (ΔHbO_2) time series measured using fNIRS and high-frequency electrical oscillations measured using EEG.

Material, Methods and Results: Three healthy participants completed three runs of an auditory task; each run included 24 blocks of six 40 Hz white noise click trains (500ms duration, 2s inter-stimulus interval (ISI)) followed by 15s of silence. EEG and fNIRS channel locations were selected to cover the frontal and left/right temporal/temporoparietal regions. Collection and preprocessing of the 15 channel EEG montage/respiration signals is described in [1], while recording of the 14 channel fNIRS montage is described in [2]. A set of regressors were generated using temporally embedded canonical correlation analysis (tCCA) as described in [3] using additional short-distance fNIRS channels and the respiration signal. A generalized linear model (GLM) was fit to the data using tCCA and task-related regressors. The estimated contribution of the tCCA regressors was subtracted from the original ΔHbO_2 signal, and a copy of the original signal was retained. EEG and fNIRS signals were filtered into frequency bands of interest [θ-band: 4-7 Hz, α-band: 7-14 Hz, β-band: 15-30 Hz, and γ-band: 30-55 Hz for EEG; very-low frequency (VLF): 0.07-0.2 Hz and low-frequency (LF): 0.2-0.5 Hz for fNIRS] and the Hilbert transform of both signals was taken.

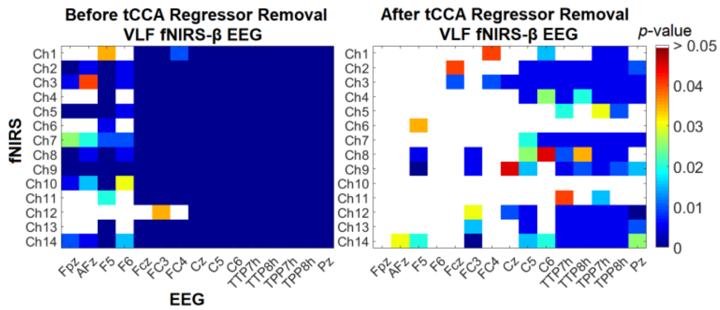

Figure 1. p-value maps of phase-amplitude coupling (PAC) between the phase of very-low frequency (VLF) ΔHbO_2 and EEG β-band power before (left) and after (right) removing tCCA regressors in one participant. Global electrovascular PAC in the original signal is reduced to local electrovascular PAC after tCCA regressor removal.

The PAC algorithm proposed by [4] was applied between the instantaneous phase of ΔHbO_2 and instantaneous EEG power amplitude (see [1]). Overall, we observed strong ($p < 0.005$) global PAC between the original VLF (0.07-0.2 Hz) ΔHbO_2 phase and EEG β-band (15-30 Hz) power across all three participants that diminished to no observed PAC in one participant and localized PAC in two others after tCCA regressor removal. Results from one participant are shown in Fig. 1.

Discussion: These results suggest that electrovascular PAC is partially driven by components of global hemodynamics. However, the presence of significant PAC after the removal of global signals from ΔHbO_2 suggests that EEG amplitude may be coupled locally with cerebral hemodynamics as well.

Significance: These results identify global electrovascular coupling and provide insights into the potential sources of this phenomenon, which may inform subsequent hybrid EEG/fNIRS studies.

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Calibration methods during EEG signal acquisition and their impact on motor imagery decoding

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Introduction: Motor imagery (MI) based brain-computer interfaces (BCI) enable users to spontaneously send a command to a device by imagining a movement [1]. To reliably decode MI for an individual, sufficient data from this person is necessary to train or fine-tune a machine learning (ML) model [2]. Furthermore, a balance between qualitative data and data that are representative of real-life conditions is desirable. However, data acquisition is a time-consuming process that currently requires the involvement of specialized technicians [3]. Improved methods for calibrating a decoding model are therefore necessary to ensure reliable decoding and an optimal user experience.

The aim of this research is to develop a calibration procedure that is both user-friendly and effective. For this purpose, the amount of data that is necessary to achieve satisfactory decoding accuracy without over-fitting and finding the best approach to calibration regarding user experience were investigated.

Materials and Methods: Electroencephalography data were acquired from 15 participants (14 male, 1 female) aged between 18 and 50 years. Each participant visited the laboratory for 5 sessions. The first two sessions were familiarization and the remaining sessions consisted of data gathering with feedback. Feedback entailed a textual cue indicating whether the predicted movement matches the requested movement. Several ML models using common spatial patterns and linear discriminant analysis were trained on data from individual participants and fine-tuning methods that also include data from other participants were investigated.

Results: Using data from individual participants, an average decoding accuracy of 0.67 was achieved using 15 training samples per movement without feedback and 8 samples per movement with feedback. The decoding accuracy greatly varies between individuals with a standard deviation of 0.15 and a maximum and minimum of 1.0 and 0.33 respectively.

Discussion: The results show that it is possible to train an MI decoding model with limited data. However, due to variability in the data and changes in the users signals over time, multiple recalibrations will likely be necessary. Hence, it would be advisable to focus future research on making the calibration process practical and feasible for the user, and automatically detecting when recalibration is necessary while limiting the calibration time.

Significance: Introducing a new user to a BCI control system should be a straightforward process that the user should be able to perform without any assistance beyond donning the recording equipment. Therefore, determining the optimal methods for user calibration, with a focus on user experience should be an essential step towards real-life BCI control systems.

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What can we learn from user interviews in BCI sessions?

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Introduction: What factors contribute to the success of motor imagery training for novice users of EEG-based Brain-Computer Interfaces (BCI)? How do novice users experience and adapt to Kinesthetic Motor Imagery (KMI) training? One way to find out more is to ask the users themselves and to collect qualitative data with interviews during BCI sessions. However, the practice is not common, although it tends to be more democratized in recent literature, mostly with patients [1—10].

Methods: Semi–structured interviews were conducted at the end of each of three BCI training sessions for 24 individuals, for a total of 72 interviews. The interview questions covered performances, difficulties and strategies, i.e. movements that users chose to imagine for KMI. The questions were designed to clarify users' choices, the reasoning behind them, and identify any barriers they encountered during the training. Interviews were analysed to identify any training parameters that users found difficult or distracting, which is a lever to better understand users' needs and to ultimately design better exercises for the future of BCI user training [11].

Results: Thematic analysis showed important inter–individual discrepancies. While some user struggled to find strategies, others found it easy. Similarly, KMI was difficult for some users, but many others explained that the KMI was not difficult per se. Still, users tend to report quick improvements in their KMI auto–evaluation within and between sessions.
Overall, this series of interviews highlighted various issues with common training protocols, some well–known, but that may not receive enough attention within the community. This includes:

- Users tend to be prone to overthinking, and they struggle to go or stay in a relaxed state.
- BCI requires focus, fighting fatigue, and coping with bad performances.
- Handling artefacts and avoiding movements is difficult and consumes attention.
- Eyes–open imagination is hard, especially with continuous feedback.
- Inter–trial duration can feel too short, and MI can be hard to maintain over the trial duration.
- Some MI tasks may implicitly involve other body parts and interfere with right/left separation.
- Users do not always contain their curiosity and sometimes can show unexpected behaviours such as disobeying instructions.
- Understanding feedback is hard, notably identifying min/max and assimilating sham feedback.
- Contextual factors can strongly affect the KMI experience, e.g. room temperature.

Discussion/Significance: Interviews were conducted with healthy users over their three first BCI sessions. Although results might not apply well to all populations, they suggest overall that BCI training is highly demanding and causes users to struggle despite high motivation. This emphasizes the need for the development of more engaging and effective training approaches that help novice BCI users explore the interaction, understand instructions and feedback, and maintain focus during training.

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Differentiable learning of image encodings for cortical visual neuroprosthetics through bio/phenomenologically-aware phosphene modeling

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Introduction: The development of high-channel count intracortical neuroprostheses for the blind[1], alongside recent demonstrations of these systems in human patients[2], establishes the possibility of restoring a rudimentary form of vision. Alongside these developments, the interdisciplinary field of neurotechnology is met with a wide array of challenges. Among these is the task of creating meaningful visual representations constrained by a limited implant resolution and safety and hardware constraints.

In order to gain insight on phosphene vision (i.e. creating artificial light percepts by electrically stimulation of the brain), simulated prosthetic vision grants researchers the ability to generate and test scientific hypothesis allowing for the optimization of computer image algorithms that are designed/trained to generate useful visual representations for the users [3], [4]. Here, we demonstrate how we can learn to create meaningful image representations using cortical phosphene representations in a biologically plausible way. In order to do that, we integrate decades of research evidence on modeling the effects of electrical stimulation on cortical tissue, coupled with electrophysiology and psychophysics data, into a novel, phenomenologically realistic differentiable artificial vision simulation pipeline.

Material, Methods and Results: An integrative model of phosphene perception, accounting for a wide array of psychophysical and neuroscientific evidence such as cortical magnification, current spread, phosphene thresholds, the relationship between electrical stimulation parameters and phosphene brightness, size, and temporal dynamics - including phosphene fading effects- is developed. Implemented in Pytorch, this model of phosphene perception, linked to computer vision algorithms based on Deep Neural Networks, allows for differentiable end-to-end learning of phosphene-based image representations on a broad diversity of conditions. These include realistic safety stimulation constraints, dynamic encoding of video data, and encoding of naturalistic images, in real time on a single GPU.

Discussion: While the neurophysiology and psychophysics of phosphene vision regarding cortical neural implants is still on its developmental beginning, an integrative pipeline able to create biologically and phenomenologically realistic cortical simulated prosthetic vision is a Prerequisite for the creation of when creating useful visual representations. Our simulations show highly correlated predictions with respect to the empirical psychophysics literature. In addition, the differentiable nature of our proposed modelling and optimization approach allows for deep learning-based end-to-end optimization of phosphene-based visual representations tailored to realistic physical and safety constrains.

Significance: A machine learning-compatible, realistic model of cortical phosphene perceptions enables neuroscientists, neuroengineers and clinicians to narrow the gap between prosthetic vision research and clinical applications.

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Pole tracking of EEG signals for BCI applications

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Introduction: Autoregressive (AR) models have been widely used in brain-computer interfaces (BCI) for frequency domain characterization of the electroencephalogram (EEG) signals. The coefficients of the AR models have also shown high discrimination capabilities. Time-varying AR analysis is usually achieved by segmenting the EEG into quasistationary epochs. Subsequently the estimated coefficients or the AR power spectral densities are used for classification or analysis purposes. This approach, although very popular, is limited by the selection of an optimal window length. A small window could lead to high estimation variance, whereas a large window would smoothen out fast/abrupt changes. To overcome this challenge, recursive techniques such as Kalman filtering (KF) and Recursive Least Squares have been proposed to track the evolution of the AR coefficients. The main issue with these techniques, however, is stability as well as interpretability of the model coefficients. A more intuitive approach would be the direct tracking of the poles of the AR model. The frequency and the magnitude of the poles describe in a compact manner the spectral characteristics of the analysed signal. Pole tracking (PT) relies on reformulating the AR model as a cascade of first- and second-order filters. This allows independent monitoring of the poles of each filter. However, the model becomes nonlinear in its coefficients and therefore, we have previously used the unscented KF (UKF) for its time-varying estimation [1].

Materials, methods and results: We applied PT on the Graz data set A of the BCI competition 2008 [2], consisting of 22-channel EEG signals obtained during cue-based movement imagination of the left hand, right hand, tongue and both feet. Our goal was to explore the possibility of classifying these movements using as features the frequency and the magnitude of the tracked EEG poles. For each subject and each trial, we extracted five poles from channels Fz, Cz, C3, C4 and Pz (one pole per channel). The UKF hyperparameters were optimized based on only one trial (from each subject) and then kept fixed for the rest of the trials. The average testing classification accuracy over time for four representative subjects can be found in Fig.1A. At each time point we applied shrinkage Linear Discriminant Analysis classification [3] based on a 10-fold cross-validation scheme. As features we included the instantaneous amplitude and frequency of the tracked poles from each channel (i.e., overall 10 features). The time evolution of a representative pole for different imagined movements can be seen in Fig.1B,C.

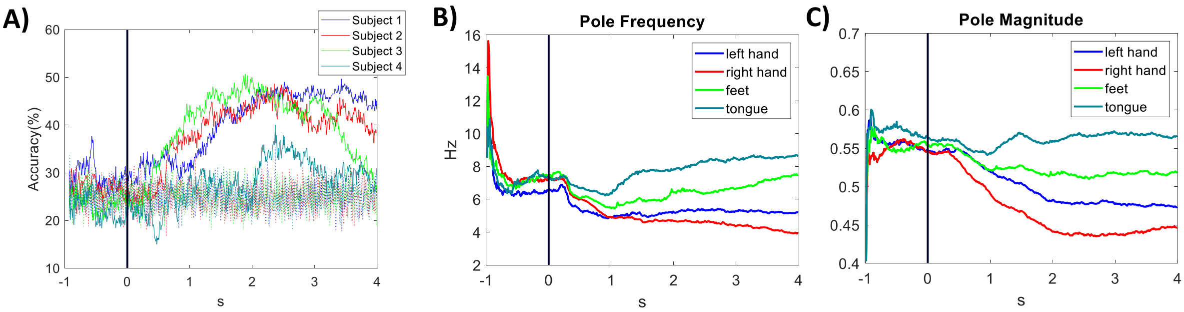

Figure 1: **(A)** Classification accuracy throughout time in four subjects and average (over all trials) evolution of the **(B)** frequency and **(C)** magnitude of the C3 pole from one representative subject for the different types of movement imagination. The black vertical line denotes the cue onset. In (A) dotted lines (around ~25% level) represent the chance level obtained by permuting randomly the input feature vector.

Discussion and Significance: We have proposed the use of AR PT for spectral characterization of EEG signals in a BCI dataset. This technique allows for real-time monitoring of the poles of the EEG without the need of applying sliding windows. We observed that one pole for each channel was found to be sufficient to describe the underlying dynamics and this could be projected on the classification results. However, in future work we will investigate the impact of a larger number of poles. UKF hyperparameter tuning was achieved using only one trial, which is a highly favorable attribute when calibration time is required to be minimum. Most importantly, however, the time-varying pole features can be further used to understand in more detail the EEG characteristics that different imagined movements give rise to.

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Coordinated arm movements are better represented in motor cortex than isolated movements

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Introduction: Natural reaching entails the coordinated movements of joints distributed over the entire upper limb – including the arm and hand. Furthermore, individual neurons in M1 carry “multiplexed” signals associated with the coordinated control of both hand and arm movements [1]. Despite this, brain-computer interface (BCI) decoders for restoring upper limb movement have been trained with isolated movements of the arm, wrist, and hand [2]. Decoders trained on (attempted) isolated movements may not generalize well to tasks requiring coordinated movements, yielding slower actions than those of able-bodied individuals [2]. Here, we show that calibration paradigms that include coordinated (imagined) movements of joints distributed across the entire limb yield decoders that can accommodate both coordinated and sequential movements.

Material, Methods and Results: A participant in an ongoing clinical trial for intracortical BCI control of a robotic prosthetic limb attempted to perform a sequential movement task and a simultaneous movement task. During the sequential movement task, the hand moved to a target, which then changed orientation. The wrist then rotated to accommodate the object’s new orientation. During the simultaneous movement task, the object was presented at a new location and orientation and the hand moved to the location and the wrist rotated appropriately in one smooth motion. We fit a linear 6D velocity encoding model to each set of neuronal responses and compared their ability to predict the responses obtained in the other set. We found that models fit to neural responses obtained during the simultaneous movement task could predict responses obtained during the sequential task but the converse was not true (Fig 1A). We also fit decoding models to each data set. Again, the simultaneous data yielded kinematic decoders that generalized to the sequential task, but the converse was not true (Fig 1B).

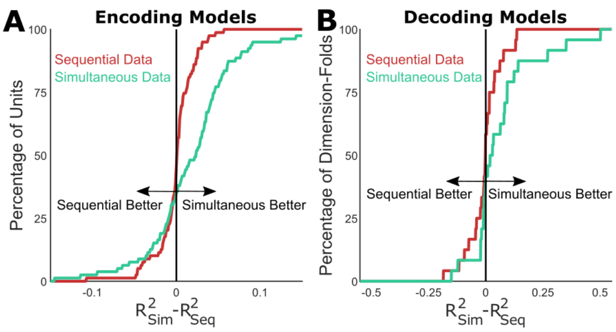

Figure 1. Coordinated movements evoke more recognizable activity in motor cortex. A) The linear encoding model explains evoked firing rates much better for most channels when fit on simultaneous movements. B) Similarly a decoder trained on simultaneous movements is much better at explaining simultaneous movements, and no worse at explaining sequential movements.

Discussion: When the BCI user attempted to move the wrist and arm at the same time, the evoked neural population yielded encoding and decoding models that generalized to actions where proximal limb and wrist moved sequentially. However, the inverse was not true, indicating that understanding the representation of coordinated movement is important to producing improved BCI decoders.

Significance: Training kinematic decoders on more naturalistic movements, which entail the coordination of joints distributed over the entire arm, will enable BCI users to perform more naturalistic movements and complete a wider variety of tasks.

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Care professionals' perspectives on BCI needs in children and adolescents with severe cerebral palsy

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Introduction: For some children with cerebral palsy (CP) communication can be severely impaired. Brain-Computer Interfaces (BCIs) are a potential communication solution for these children. Yet, the actual need for this technology among these children, including their perception on the opportunities, is unclear. Therefore, the current project aims to map the needs, wishes and opportunities of BCIs for children/adolescents (8-25 years old) with severe CP (Gross Motor Functioning Classification System level IV and/or V; 'the target group') regarding communication. To that purpose, we assess the perspective of three populations: 1) the target group, 2) their parents/caregivers, and 3) involved care professionals. Here, we focus on the perspectives of care professionals.

Material & Methods & Results: To explore the perspectives of care professionals, online surveys were used, consisting of three sections: 1) demographic data, 2) current communication aids, and 3) BCIs. Thirty-six care professionals have completed the survey (34 female, 1 male, 1 unknown; age M=44.6 years, SD=11.01; years of experience with target group M=15.89 years, SD=10.16; 34 respondents still work with the target group, 2 in the past). Satisfaction with current communication methods (i.e., [a] no device (e.g. eye-gaze) or a letterboard/-book, [b] simple speech computers, and [c] high-tech communication equipment) was rated on a 5-point Likert scale (1=very unsatisfied, 5=very satisfied; [a] n=34; [b] n=25; [c] n=33). For respondents familiar with all three methods (n=24; [a] M=3.00, SD=0.78; [b] M=3.13, SD=0.85; [c] M=3.58, SD=0.65), a repeated measures ANOVA revealed a significant difference in the mean satisfaction scores between these three methods ($F_{(2,46)} = 4.850$, $p = .012$). To specify, the mean score for method C was significantly higher than for method B ($F_{(1,23)} = 6.457$, $p = .018$). No significant difference was found between the latter compared to method A ($F_{(1,23)} = .418$, $p = .524$).The majority (77.8%) of the care professionals was interested in BCI for the target group (e.g., allowing faster communication, increase autonomy and decrease frustration). When asked about which BCI control strategy is most suitable, 38.9% of the respondents scored P300 higher (=more suitable) than motor imagery on a 5-Point Likert scale, 38.9% rated them equally, and 22.2% vice versa. In addition, 41.7% of the respondents scored implanted recording electrodes higher than external electrodes on a 5-Point Likert scale, 36.1% rated them equally, and 22.2% vice versa. Non-parametric paired t-tests (Wilcoxon Signed Rank Test) revealed no significant differences in mean scores for either the BCI control strategy (p=.318; P300 M=3.47, SD=1.00; motor imagery M=3.22, SD=1.05) or the type of recording electrodes (p=.150; external M=2.97, SD=1.00; implanted M=3.36, SD=1.10).

Discussion & Significance: Knowledge on the perspectives of the different types of end-users and stakeholders is crucial to assess the need for alternative communication strategies for young people with CP, and to develop clinically viable BCI technology. The first results of this study indicate that most care professionals involved with the target group are interested in BCIs as a communication solution. Their preferences for the different BCI approaches are variable. In order to better understand the perspective of this group, we will perform a qualitative analysis of the open questions included in the questionnaire.

Acknowledgements: The videos in the surveys were created by Merel Horsmeier, voice-over by Marline van der Meer. The images in the surveys were created by Merel Horsmeier and Malinda Verberne.

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EEG indices of responsiveness in Minimally Conscious State

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Introduction: Minimally Conscious State (MCS) is a clinical condition characterized by reproducible, but inconsistent signs of consciousness [1]. Fluctuations of responsiveness contribute to the misdiagnosis rate and prevent from effective interactions with MCS patients [2]. These clinical fluctuations might also greatly limit the use of any Brain-Computer Interface (BCI) for communication purposes. The objective of the present study was to identify neurophysiological indices of responsiveness in MCS patients, investigating the connection between EEG background activity and the presence of a P300 ERP (*Event-Related Potential*) response to an oddball paradigm, considered a sign of higher level of responsiveness with respect to its absence [3].

Material, Methods and Results: EEG (19 channels, sampling frequency 250Hz) was recorded from 16 MCS patients (6 females; mean age±standard deviation=44.0±15.9) during a 5-minute resting-state period, followed by an auditory passive oddball paradigm. According to the visual inspection of the ERP waveforms elicited by the oddball paradigm, patients were divided in two groups based on the presence ("P300" group; n=9) or not ("no P300" group, n=7) of the P300. EEG data were pre-processed and spectral indices were extracted to characterize EEG background activity. In particular, we considered relative powers in three frequency bands (delta, theta, alpha), the theta/beta ratio (TBR), the median frequency and the spectral edge frequency (SEF). Independent samples t-test was used to compare spectral indices between the "P300" and "no P300" groups. Results reported in Figure 1 showed that the TBR in Cz (t=2.24; =0.042) and in Fz (t=2.20, p=0.047) and the SEF in Cz (t= -2.97, p=0.01), resulted significantly different between the two groups.

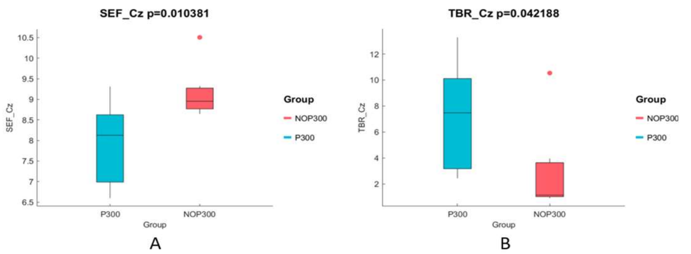

Figure 1. *Boxplot representation of the significative differences between the "P300" and the "no P300" groups in the SEF and in the TBR in Cz.*

Discussion: Our results showed that TBR and SEF indices in the resting state are related to the presence/absence of the P300 in an oddball task; this highlights the possibility to disambiguate responsiveness of MCS patients from the EEG background activity. Such disambiguation would represent a step toward the characterization of the EEG background activity related to the fluctuation of responsiveness and to the identification of a responsive period suitable for interaction with patients.

Significance: Although preliminary, these results support the possibility of identifying neurophysiological indices of responsiveness within the fluctuations in MCS patients. This would sustain the rehabilitation process and the implementation of a "timely" BCI to support the interaction with MCS patients.

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Re-Configuration of Resting State Brain Networks after BCI training in subacute stroke patients

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Introduction: Motor imagery (MI) practice within a BCI-assisted rehabilitative intervention proved to influence brain plasticity phenomena underlying post-stroke motor recovery as outlined by resting state (RS) brain networks analysis based on graph theory (GT) approach [1]. We investigated RS networks in a subgroup of stroke patients recruited within a longitudinal randomized controlled trial evaluating the efficacy of a MI-based BCI on upper limb (UL) motor rehabilitation [2] describing brain re-organization at the single subject level.

Material, Methods and Results: High resolution EEG data (61 channels, sampling frequency of 200Hz) were acquired during 2 minutes of open-eyes rest in 16 post-stroke patients (8 BCI, 8 CTRL) before (T0) and after (T1) the intervention. Patients in the BCI group underwent 1 month of BCI-supported UL MI training, while CTRL group received equally intense MI training without BCI. The UL function, as assessed via the Fugl-Meyer Assessment (FMA), improved in both groups from T0-T1 (BCI 15±16.60 - 25±21.13; CTRL 15±15.27 - 19±19.12). RS brain networks have been estimated in 5 frequency bands by means of Partial Directed Coherence (PDC) for each patient in the two groups and each timepoint. Graph theory indices characterizing RS networks were computed and subjected to a two-way mixed ANOVA considering TIME (T0, T1) and GROUP (BCI, CTRL) as within and between factors, respectively. Results in Figure 1 showed a significant increase in the connections density as for alpha frequency oscillations between the two hemispheres ($F= 8.3378$, $p= 0.02$) and the anterior and posterior areas ($F=6.8306$, $p=0.020431$) in BCI group after the intervention. No changes were found for the CTRL group.

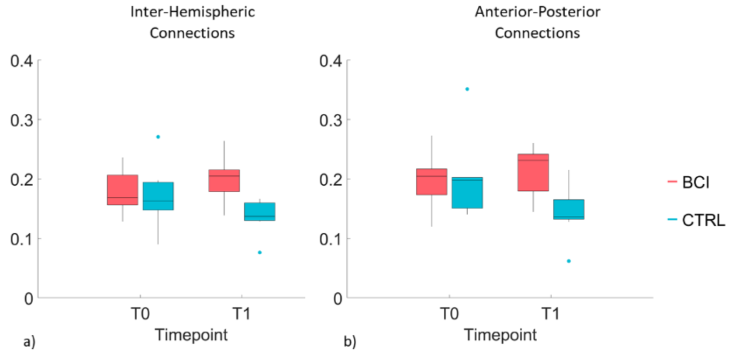

***Figure 1.** Boxplot reporting graph theory indices distribution obtained for RS networks estimated in alpha band at T0 and T1 in the two groups: a) inter-hemispheric connections and b) antero-posterior connections.*

Discussion: Despite the preliminary nature of our findings (ie. small sample size) we were able to highlight significant changes in GT indices estimated at single subject level, which are in line with previous literature findings [1,3]., likely induced by the training yet unrelated to the task which potentially extends to other functions and contexts (eg. other than UL recovery).

Significance: The observed changes in RS brain networks depict a modified neural configuration, whose correlation with functional outcome will be investigated further as the clinical trial progresses. Stratification allowed by the increased sample size (eg. moderate vs severe patients) will eventually allow to identify brain network properties which best correlate with a favorable motor outcome.

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The role of agency in neurofeedback performance

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Introduction: Neurofeedback (NF) aims to elicit voluntary modulation of neural activity by providing online feedback (FB). In Motor Imagery (MI) NF, participants reduce sensorimotor activity by imagining movements. Providing FB improves modulation relative to simple MI [1]. Yet, a lot of NF participants fail to learn to modulate targeted activity [2]. Most studies feature abstract FB obscuring the causal link between the MI task and the FB. This may reduce the sense of agency, which is rooted in the consistency between predicted and actual sensory outcomes [3]. FB transparency could increase this consistency, yielding better sense of agency and in turn better NF performance. In this study, we tested this hypothesis in a MI-NF EEG-based protocol with different FB conditions.

Material, Methods, and Results: 23 participants performed right-hand MI with EEG recording (32 active electrodes). They received online FB through three conditions: a pendulum, a virtual hand, a virtual hand and vibrotactile stimulation inducing motor illusion. The amplitude of the pendulum and virtual hand movement was proportional to online β power (8-30Hz) reduction over C3 (above left motor cortex), relative to β reference level at rest. There were 10 NF trials of each condition. We included control conditions of MI alone (without FB) and passive observation of FB stimuli (without MI).

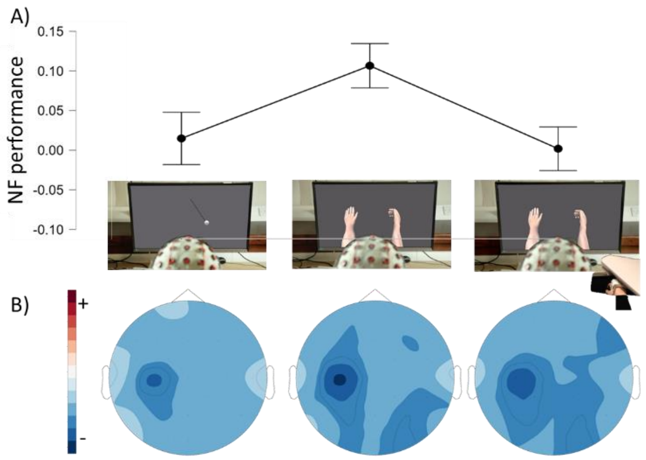

Figure 1. A) NF performance as a function of FB condition (pendulum / virtual hand / virtual hand plus vibration). *Plot of the overall mean NF performance across subjects. Vertical bars = standard error of the mean.*
B) Topographical maps of the ERD in the β band for the 3 FB conditions. *Overall mean of the 23 subjects.*

Participants showed best NF performance with the virtual hand (**Fig 1**). This translated into a stable β reduction pattern during and across trials for this condition. In contrast, the other conditions yielded lower performance that rapidly degraded across trials. Agency was highest in the virtual hand condition. Mediation analysis showed that agency fully mediated the effect of FB transparency on NF performance. In addition, time-frequency analysis showed that event-related desynchronization (ERD) was more focal with the virtual hand than the pendulum and the virtual hand plus vibration conditions, peaking on C3 in the 12-15 Hz SMR frequency band. Control condition analyses showed that this effect was not merely due to the visuo-tactile stimuli used as FB and that MI alone was not sufficient to reduce online β power.

Discussion/significance: Our results suggest that feedback transparency allows better NF performance mediated by agency. Spatio-frequential patterns suggest that practicing with virtual hand FB allows to selectively downregulate SMR activity over motor cortex. These results have important implications for the development of MI NF protocols that foster learning.

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Co-adaptive BCI based on supervised domain adaptation: results in motor imagery simulated data

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Introduction: Brain-computer interfaces (BCIs) can be thought of as a two-learners system, in which the user learns how to control the computer and, simultaneously, the computer learns how to decode the user's brain activity [1]. When used across several sessions, as in motor imagery (MI) BCIs for rehabilitation, the recorded EEG signals contain high variability. Machine learning systems used to decode brain activity should then adapt to those signal changes and help the user in the development of stable EEG patterns. In this line of work, a backward formulation of optimal transport for domain adaptation (BOTDA) was proposed in [2] to avoid recalibration in cross-session MI-BCIs. Although BOTDA showed promising results in a supervised sample-wise scenario, it remains to be elucidated whether the success of the adaptation depends on the subject's ability to perform the MI task or on the adaptive capabilities of the model. Here we hypothesize that supervised adaptation based on BOTDA is successful only when: **H1)** the EEG patterns provided by the user corresponds to the mental task to be performed and **H2)** the calibration data, used to train the decoding model, is discriminative enough from the decoding system viewpoint.

Material, Methods and Results: Considering MI-BCIs for motor rehabilitation, realistic MI vs. Rest EEG data was generated based on a custom implementation that extends [3]. MI alpha desynchronization (aka ERD) was simulated in the left hemisphere for MI. "Rest" corresponded to no-ERD. We used the first session (S1) to train the model (calibration data) and the following session (S2) was used as testing data. For each session, 100 trials of each class were simulated. As a decoding algorithm, a common spatial pattern and a linear discriminant analysis were used, as in [4]. To prove H1 we simulated S1 as the ideal case, i.e the ratio between ERD and baseline amplitudes (%ERD) was set to 50 for all trials belonging to the MI class (0% of failed MI trials). Results show that BOTDA can provide almost perfect classification accuracy (ACC) regardless of the %ERD in S2 (e.g. ACC=0.97 with BOTDA, ACC=0.51 without BOTDA for a S2 with %ERD=10). Experiments varying the percentage of failed MI trials, but with high %ERD, indicated that BOTDA could not help with failed trials (e.g. ACC=0.76 with BOTDA, ACC=0.76 without BOTDA for a S2 with %ERD=45 and 50% of failed MI trials). To validate H2 we trained the decoding model with data from sessions with different %ERD values. We found that when the simulated calibration data did not contain discriminable ERD patterns (%ERD<20, calibration ACC<0.7), the test ACC always yielded by-chance levels.

Discussion: Results on these simulations show that BOTDA can be a valuable tool for building co-adaptive MI-BCI systems, in which calibration data must meet a minimum accuracy of 70% and users need to present some %ERD reflecting correct responses to the indicated mental tasks.

Significance: Supervised adaptation based on BOTDA can help the user during the learning process of commanding a MI-BCI.

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Detecting fluctuation of responsiveness in Minimally Conscious State patients

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Introduction: A Minimally Conscious State (MCS) is a disorder of Consciousness (DOC) showing a within/between subject (spontaneous) variability of clinical signs of responsiveness [1]. Such fluctuations in responsiveness could prevent patients to access the Brain Computer Interface (BCI) to interact with the environment. MCS patients, indeed, could show time windows of responsiveness in which they can potentially communicate (Windows of responsiveness; WoR) and time windows in which they cannot. The objective of this study is to describe the fluctuation of responsiveness by identifying the neurophysiological response (presence/absence of WoR) to an oddball and a motor task within a continuous EEG monitoring.

Material, Methods and Results: Three patients (M=3; age=43±21) with MCS underwent two sessions (morning 2 hours, afternoon 2 hours) of continuous EEG monitoring (32 channels) in resting-state lasting (4 hours of recording in total). An auditory oddball task and a motor command task were presented five times each, in each of the two sessions, with a random interval (range 9-11 min). We identified the presence/absence of the WoR based on the response detection in the two tasks (Figure 1B-C). As for the motor command task, we labeled the WoR by statistically comparing (unpaired t-test, $\alpha=0.05$) the power spectral density in task and rest conditions: a significant desynchronization of the sensory-motor rhythms (SMR) in alpha and beta bands defined the presence of a WOR. Sleep was monitored by means of a behavioral observation and EEG background activity analysis. For the oddball task we labeled as WoR the time slot where the P300 component was identified in the target/non-target difference. Figure 1-A reports the WoR observed for each participant within the EEG monitoring. One of the three subjects showed 7 blocks labeled as WORs, while 2 subjects showed three WORs.

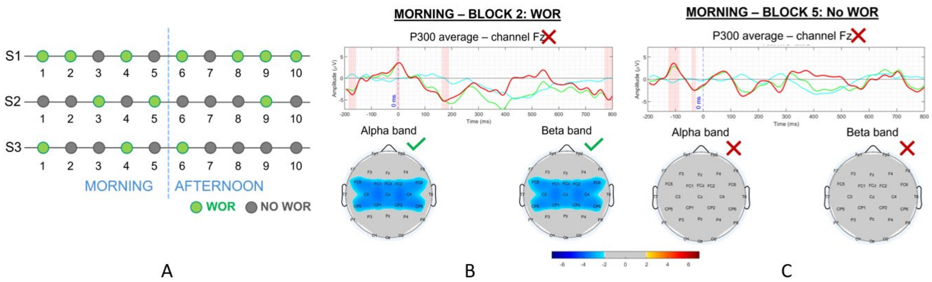

Figure1. *A-WoRs observed (green) for each participant within the EEG monitoring. B, C-Morning session, subject 1, WoRs evaluation examples: in panel B (block 2), despite the lack of a visible P300 response, a WoR was accounted through the presence of a significant desynchronization of the sensory-motor rhythms both in alpha and beta bands. On the contrary, in panel C (block 5,) no WoR was identified due to the lack of either a visible P300 response, or significant desynchronizations of the sensory-motor rhythms.*

Discussion: Our preliminary results showed the presence of a fluctuation in P300 and SMR responses to the presentation of an oddball and a motor command task respectively. We speculate that, the probability of a successful interaction with the patient by means of a BCI in the WoR time slot would be higher than in the non-WoR slots.

Significance: Development in BCI field has been devoted to instantiate communication of patients with no other way of communication. These preliminary results represent the starting point in reversing the BCI perspective by focusing on the identification of the best moment to propose a BCI for communication to the MCS patients (WoR).

Acknowledgments: The work was partially supported by the Italian Ministry of Health, under the Programme Giovani Ricercatori 2019 (Project No: GR-2019-12369824).

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Identifying the best candidates for a rehabilitative BCI targeting upper limb motor recovery.

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Introduction: Randomized Controlled Trials (RCTs) in the last decade have shown the benefits of BCIs for post-stroke motor recovery of the upper limb (UL) [1]. The paradigms are heterogeneous in terms of tasks (eg. Motor Imagery, MI vs motor attempt), feedback modalities (eg. visual vs haptic) and training protocols. As of today, there is no consensus on which BCI approach is best for which type of patient. We are conducting a RCT [2] to investigate the long-term effects of MI-based BCI with visual feedback on UL motor recovery and identify the best candidates among subacute stroke patients.

Material, Methods and Results: The study protocol foresees the enrollment of 48 patients undergoing rehabilitation after a recent (<6 months) ischemic/hemorrhagic stroke; deficit in the affected UL is assessed at enrollment (T0) as moderate or severe according to the Fugl-Meyer Assessment (FMA) (mildly affected patients excluded) and the Action Research Arm Test (ARAT). Patients are randomized into BCI and CTRL groups, performing respectively 12 sessions of BCI-supported UL-MI training or MI-training without BCI. The FMA and ARAT are repeated post-training (T1) and after 1, 3 and 6 months (T2, T3, T4). Figure 1 shows trends of FMA improvement in BCI and CTRL groups for severe and moderate patients. Qualitatively, the curves differ especially in the severely affected patients, in favor of the BCI intervention. Statistical analysis (Friedman test) at this stage of enrollment could be performed in severe patients only, showing significant improvements in FMA for both BCI (χ^2 = 25.04, p=.00005) and CTRL (χ^2=12.76, p=.013) groups, while significant improvements in ARAT are observed for the BCI group only (χ^2=20.77, p=.00035).

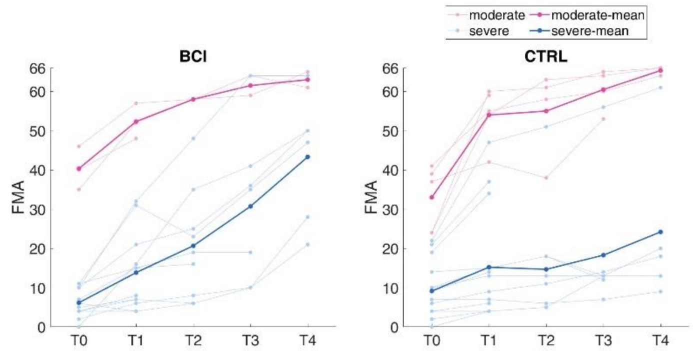

***Figure 1.** FMA values at the different timepoints for severe (blu lines) and moderate (pink lines) patients in the BCI and CTRL groups.*

Discussion: Preliminary findings of the RCT suggest that MI-based BCI with visual feedback could be particularly useful in stroke patients with severe UL motor deficit. For these patients, MI within a BCI paradigm provides the unique opportunity to exercise the otherwise inaccessible motor system with contingent feedback. The benefits obtained via the BCI training early in the rehabilitation process allow them to eventually access other rehabilitation approaches (which require some level of motor function) and thus exponentially improve UL motor outcome along the subsequent timepoints.

Significance: While the efficacy of BCIs for post-stroke motor recovery has been sufficiently demonstrated against sham/control interventions, little is known on how to address specific BCI based intervention to those patients' categories that will benefit the most. This aspect is crucial to direct resources of private and public stakeholders and thus foster actual translation of research results into clinical practice.

Acknowledgements: Partially supported by the Italian Ministry of Health (RF-2018-12365210, GR-2018-12365874).

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Toward Hybrid BCI: EEG and Pupillometric Signatures of Error Perception in an Immersive Navigation Task in VR

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Introduction: Brain-Computer interfaces (BCIs) frequently incorporate the detection of erroneous events to improve their performance. This detection is usually exclusively based on electroencephalographic (EEG) correlates of error perception [1, 2]. Head-mounted displays (HMDs) with built-in pupillometric sensors allow for access to additional physiological data with the potential to improve error detection [3].

Material, Methods and Results: We used an HP Reverb G2 Omnicept HMD to display the virtual reality (VR) flight simulation and to measure the pupil size of 19 participants. Additionally, we measured EEG signals using 61 active electrodes. The participants were asked to navigate a glider through targets in VR (see Fig. 1), as three different types of erroneous events were randomly triggered: (i) the target suddenly changed its position (condition *target*), or (ii, iii) a torque was applied to the glider resulting in an unexpected rotation of it. The last could happen either while the participants actively steered the glider (*active*) or were in a passive state (*passive*). In *correct* trials, no error was triggered. EEG data preprocessing included filtering (non-causal, 1-10 Hz), eye-artifact correction, rejection of corrupted trials, and common average referencing. After we applied the false discovery rate procedure to correct for multiple testing, we found statistically significant differences in the EEG and pupillometric data. Fig. 1 shows the averaged evoked responses calculated from the participant averages.

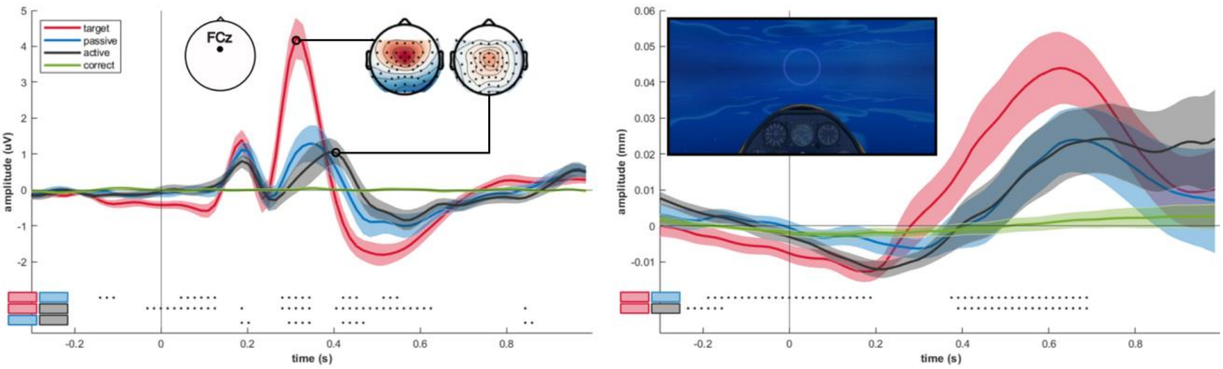

***Figure 1**. Grand average results. Left: Error-related potentials (± standard error) for the three error conditions and the correct condition. The dots below the signals show significant samples ($p < 0.05$) for the comparisons indicated by the rectangles. Errors were triggered at $t = 0$ s (vertical line). Right: Baseline-corrected pupil dilation (like on the left) and the flight simulation (glider approaching a target).*

Discussion: In the evoked EEG responses, we found that performing a task delays the error perception (*passive* vs. *active*), illustrated by the significant differences in the corresponding error-related potentials. Additionally, we found a dilation of the pupil induced by the erroneous event with a similar delay.

Significance: We argue that, based on our results, pupillometric correlates of error perception have the potential to improve the performance of BCIs in immersive virtual environments.

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A comparison of stimulus sequences for code-modulated visual evoked potential (c-VEP) based BCI

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Introduction*:* The code-modulated visual evoked potential (c-VEP) is an evoked response observed in the EEG in response to rapid visual stimulation with a pseudo-random sequence of flashes [1]. Contrary to ERP protocols, c-VEP stimulation is faster. Opposed to SSVEP protocols, c-VEP stimulation is non-periodic. Consequently, c-VEPs allow higher bandwidth. To make full use of the potential of c-VEPs, it is important to consider the vast choice of stimulus sequences. Typically, sequences from telecommunication are used like m-sequences or Gold codes [1]. However, it is often ignored that these sequences are optimized in the digital stimulus domain, while good BCI performance largely depends on good correlation properties in the EEG response domain. Carry-over between these domains is not a given. Unfortunately, however, to date there is no good understanding of which stimulus sequence leads to optimal BCI performance.

Material, Methods and Results*:* We recorded 64-channel EEG data from 16 participants who were shown a 4x8 matrix speller with 10 different stimulus sequences at 60 Hz. Code-families were (1) a shifted m-sequence, (2) a shifted Gold code, (3) a set of Gold codes, (4) a shifted de Bruijn sequence, and (5) a shifted Golay sequence. Codes were presented as either original or as modulated via XOR with a double-frequency bit-clock to limit low-frequency content [2]. For each condition, 32 4.2-second trials were recorded to offline estimate decoding curves using an 8-fold cross-validation with a template-matching classifier using reconvolution [2, 3] and canonical correlation analysis. The highest average information transfer rate (ITR) was obtained with an m-sequence (118 bits/min), followed by a Golay sequence (114 bits/min), Gold code (107 bits/min), de Bruijn sequence (97 bits/min) and Gold code set (82 bits/min). Additionally, overall, modulation of codes did not affect ITR compared to original codes ($p > .100$).

Discussion*:* The results suggest that the performance of a c-VEP BCI significantly depends on the sequences that are used for the stimulus protocol. Moreso, the code family that is optimal varies largely over participants, which suggests the necessity to optimise the stimulus protocol for individual users instead of the entire population of users. Such subject-specific optimization may lead to substantially higher ITRs. Further research is foreseen to gain insight into why certain stimulus sequences lead to improved performance. In turn, these insights may lead to inspiration for even better performing handcrafted stimulus sequences and ultimately faster c-VEP BCI.

Significance*:* Optimizing the c-VEP stimulus protocol for individuals leads to higher communication rates and may initiate more practical BCI applications for communication and control. Moreso, this and other improvements make c-VEP protocols a likely candidate to replace existing protocols such as ERP and SSVEP due to its obvious advantages with respect to reliability, speed, and scaling to large number of classes.

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Cortico-Muscular Coupling to control a hybrid Brain-Computer Interface for upper limb motor rehabilitation

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Introduction: Hybrid Brain-Computer Interfaces (hBCIs) for upper limb motor rehabilitation after stroke pursue the reinforcement of "more normal" brain and muscular activity. Cortico-muscular coherence (CMC) has been proved to capture motor abnormalities after stroke [1] and thus potentially be employed as a hybrid BCI feature in this context. Here we optimized the translation of CMC computation and CMC-based movement detection from offline to online.

Material, Methods and Results: EEG (61 electrodes) and EMG (8 sensors per upper limb) signals were acquired from 13 healthy subjects (HS) and 12 stroke patients during finger extension (Ext) and grasping (Grasp) performed with both hands, separately [2]. A pseudo-online analysis was performed on HS to identify the best parameters, to be set for real-time CMC computation, which allow the best trade-off between accuracy and speed in CMC-based movement detection. 4 out of the 13 enrolled HS were called back to execute an online session, in which CMC features were computed in real-time according to the best parameters identified in the previous analysis [2] and used to detect movements (Fig 1A). Overall, movements were always detected (hit rate=100%) with a delay of 480ms ± 0.04 (mean ± standard error) with respect to EMG onset. The feasibility of CMC-based movement detection was then pseudo-online tested on stroke patients. Hit rate was around 90% for Ext executed with both affected (AH) and unaffected (UH) hands, whereas it is reduced to 80% during Grasp with affected hand (Fig. 1B). Mean delay was around 580ms for both movements executed with both hands (Fig. 1C).

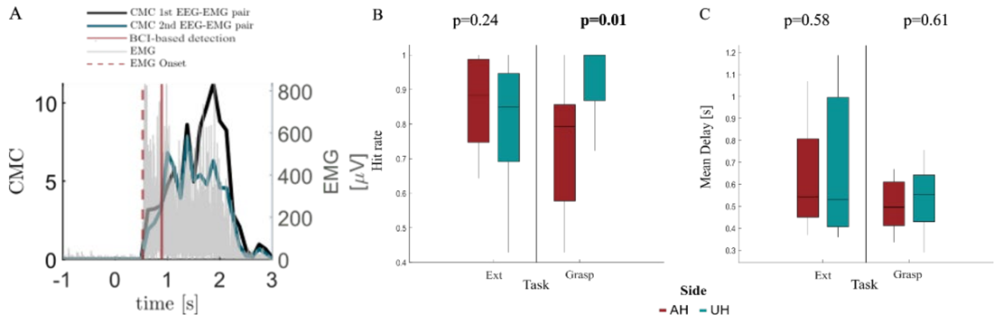

***Figure 1**. A) CMC and EMG trends in 1 healthy subject during an online movement repetition. Dashed vertical line represents movement onset detected offline from EMG (EMG onset), whereas continuous vertical line stays for the time the CMC-based BCI detected the movement in real-time. B-C) Distribution (boxplots) of pseudo-online classification performances in 12 stroke participants: hit rate (B) and a MD (C). Similar results were obtained for AH and UH in Ext whereas hit rate resulted to be lower in AH than UH for Grasp (paired t-test, α=0.05).*

Discussion: This study indicated the feasibility of CMC in detecting movements attempted by a population of stroke subjects in an accurate and timely manner. Online testing on such population is ongoing.

Significance: The results obtained will ground the design of a novel hBCI in which the control feature is derived from a combined EEG and EMG connectivity pattern estimated during upper limb movement attempts.

Acknowledgements: This work was partially supported by the Italian Ministry of Health (GR-2018-12365874 and RF-2018-12365210), Sapienza University of Rome—Progetti di Ateneo 2020 (RM120172B8899B8C).

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Assessing the impact of transcranial Direct Current Stimulation (tDCS) on the enhancement of race driving skills

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Introduction: Transcranial Direct Current Stimulation (tDCS) is a non-invasive brain stimulation approach where DC currents are delivered to the brain tissue through electrodes placed on the user's scalp, modulating cortical excitability [1]. Although tDCS seems to be a promising motor training approach, very few studies have addressed the impact of tDCS on learning complex motor skills like race driving [2]. The identification of neuromarkers associated to motor learning has begged the question whether the underlying brain plasticity mechanisms can be manipulated to give rise to faster and/or more effective training of race drivers using tDCS.

Material and Methods: Eleven novice participants were included in a study aimed at investigating the potential role of tDCS in learning to race. We recorded electroencephalography (EEG) and electrooculography (EOG) at 512 Hz using an ANT Neuro eego 64-channel EEG system while subjects were driving in a racing simulator (rFactor2). Twenty minutes of Active or Sham tDCS (PlatoWork by PlatoScience, Copenhagen, Denmark) was applied before the race-driving task. Subjects were randomly and blindly assigned to one of two tDCS groups (6 Active, 5 Sham). Balance of identified confounding factors (age, gender, driving proficiency, corrected vision) was ensured using Frane's allocation algorithm. The Active tDCS group received anodal stimulation with fixed electrode positioning designed and parameterized to assist learning by increasing neural excitability over prefrontal brain regions associated with learning. Sham stimulation simulated the same sensation without giving rise to cortical excitability. Each participant went through 10 experimental sessions (20 laps/session). Lap time was adopted as the variable for evaluating the learning outcome. Telemetry data were saved for further analysis at 100 Hz sampling rate. The role of tDCS in learning to race was evaluated through a mixed-design ANOVA with lap time gain as the response variable (average lap time of the last 2 sessions subtracted from that of the first 2 sessions), the between-subject factor was tDCS treatment (Active, Sham), and the within-subject factor was time (in sessions, with 10 levels). We also inspected the average, standard deviation, and significance (with unpaired, two-sided Wilcoxon rank sum tests) of the lap times per group and session.

Results and Discussion: The ANOVA showed no significant effect of tDCS on lap time gain ($F=0.63$, $p=0.76$). However, the session-wise lap time comparisons between the two groups suggest that tDCS may in fact play a role in learning to race. On average, Active tDCS subjects performed in the last session significantly better (by almost 3 s) than the Sham ones (Active: 89.4±9.5 vs Sham: 92.0±10.5, $p<10^{-17}$), although performance is balanced in the first session. The difference in favour of Active tDCS becomes more pronounced over sessions and is statistically significant in session 2 and throughout sessions 5-10 (see Figure 1). Interestingly, the Active tDCS group exhibits better outcomes in sessions where intense learning takes place (i.e., when the average lap improvement across all subjects is greatest). Overall, unlike all other confounds examined, the tDCS factor is the only one that is balanced at training onset and superior for the Active group at training offset, suggesting a contribution of anodal tDCS on race skill acquisition. Of note, we posit that the marginal (non-significant) superiority for the Active group observed already in session 1 should be attributed to tDCS-related learning benefits taking effect already within the 20 laps executed by subjects in the first session. It can thus be claimed that anodal tDCS seems to play a positive role in race driving learning, although the effect was not strong enough as to manifest in our ANOVA of total lap time gain in this small subject cohort.

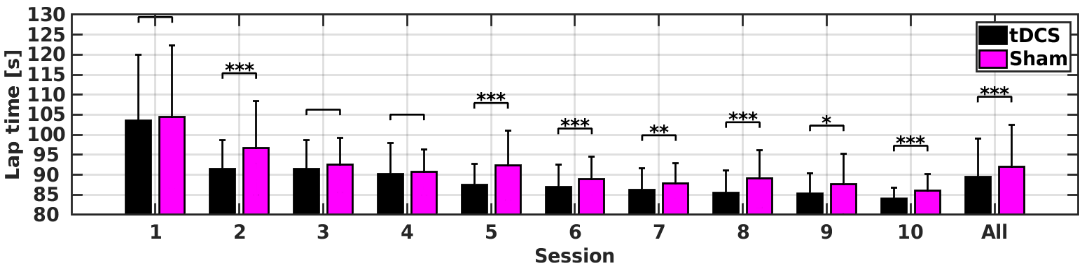

Figure 1. Average pooled lap time per session compared between two groups (Active vs Sham tDCS).

Significance: We provide preliminary evidence in favour of the hypothesis that tDCS can support learning of race driving. Future work will focus on confirming this hypothesis and delineating such effects with larger populations, as well as on studying the relationship of various EEG markers of plasticity with the learning outcomes.

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Investigating the Impact of Ecologically Valid Interactions on Rapid Serial Visual Presentation-based Brain-Computer Interface Performance

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Introduction: The Rapid Serial Visual Presentation (RSVP) is an experimental approach to BCIs in which a series of images is displayed at a high speed. Participants are asked to differentiate between a set of target images and a set of non-target images, where the P300 ERPs is evoked by the target image, but not by the non-target image [1, 2]. The automatic identification of this response in a robust way allows this paradigm to produce a functional interface relating a user's internal brain state to events in the external environment. While the RSVP approach produces impressive results in lab-based environments, translation of this technology into consumer contexts requires a better understanding of performance in ecologically valid settings, for example the use of the BCI to enhance experiences in online worlds, metaverse and gaming contexts. Such application scenarios are characterised by much less constrained user behaviour some of which is entirely necessary for the normal expected interactions we typically encounter in such applications. Examples include talking, head and hand movement. In this study we examine how such interactions induce performance degradations in an RSVP paradigm in a quantified way, explicitly articulate the signal processing challenges to mitigate this and present open datasets for researchers to benchmark performance.

Material, Methods and Results: The data collection protocol is split into two sections: 1) the standard paradigm, in which the subject performs the target search task while sitting quite still in front of the monitor; and 2) the RSVP paradigm with the induced noise, in which the participant voluntarily generates three distinct noises (i.e., walking, nodding, and talking) while doing the RSVP task. The dataset contains EEG responses to 2100 images (both target and standard images) from a single participant utilizing an Eego Sports device with 32 channels and a 1 kHz sampling rate. The participant completed three sessions consisting of six blocks per session (3 for the traditional RSVP and 3 for the RSVP with the induced noise). In each 90-second block, 360 images were displayed at a rate of 4 Hz, with 36 target images intermixed randomly among 324 non-target images.

The raw signal was passed through a band-pass filter (.5Hz to 30Hz), and then time-series characteristics were recovered from -.2s to 0.8s relative to visual stimulus onset. The common average referencing was carried out prior to the epoch extraction. Figure 1 depicts a P300 response at channel O1 in an RSVP task.

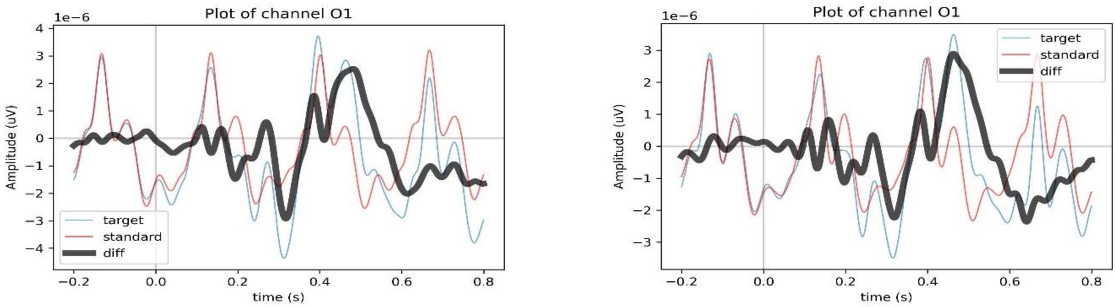

Figure 1. P300-related activity can be seen at channel 01 at around 390ms. The difference (diff) of targets (red) and standards (blue) is shown as average(target) – average(standard) in black color. The left and the right figure illustrate the traditional and the induced noise RSVP, respectively.

Discussion: The aforementioned illustration makes it evident that the P300 peak occurs at around 390ms in both scenarios. The ERP average also shows a characteristic SSVEP response.
When using an RSVP target search paradigm, the P300 isn't the only ERP that often shows up. In addition to P3, earlier ERPs like N2 and P2 are also present, and the three of them together may be quite helpful in producing discriminative knowledge for classification. In the future, we want to integrate advanced denoising algorithms that allow us to achieve the same P300 response in both a standard lab environment and a dataset with inserted noise.

Significance: In order to use a BCI system in a practical situation, it is necessary to gather information in a setting that is distinct from a controlled environment. The goal is to have such algorithms that provide the most accurate predictions possible in real time.

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UMM: Unsupervised Classification of ERPs with Confidence

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Introduction: Attended and unattended stimuli differ in the shape, amplitude and latency of the transient amplitude responses they leave in a user's brain activity. Evoked by visual, haptic or auditory stimuli, measured by magneto- or electroencephalography (MEG, EEG) and classified into attended or unattended stimulus events by machine learning methods, event-related potential (ERP) BCIs provide spelling applications or allow user interfaces to determine a desired control command. While shrinkage linear discriminant analysis (sLDA) is a widespread method for supervised classification that recently has undergone further improvements using a Toeplitz structure of the covariance [1], lately also classifiers leveraging Riemannian geometry and even neural network approaches have been investigated for ERP data in BCIs. In addition, unsupervised approaches based on learning from label proportions show promising results, however, they require a substantial warm-up period but no labeled calibration data [2]. In this work, we go one step forward by proposing **unsupervised mean-difference maximization (UMM)**, a novel classification method for ERP protocols.

Material, Methods and Results: UMM generally uses data merely from the current trial. For every available symbol $s \in S$ we can construct the *hypothesis* that s had been the attended symbol and obtain a corresponding target assignment containing all epochs of the current trial where s was highlighted, and analogously the non-target assignment. For every hypothesis s, the distance vector $\Delta\mu_s$ between the corresponding hypothetical class means is obtained. To take into account high-dimensional and noisy data, UMM employs the squared Mahalanobis distance $d^{\Sigma}(s) = (\Delta\mu_s)\Sigma^{-1}(\Delta\mu_s)^T$, which removes the influence of correlated dimensions by using the inverted global covariance matrix Σ^{-1}. The attended symbol can then be determined by $s^* = \text{argmax}\, d^{\Sigma}(s)$. As in LDA classifiers [1], we found a benefit in using a block-Toeplitz regularization of the covariance estimate in UMM. Comparing the distances of the winning assignment and the runner-up, UMM also provides a confidence metric for its decision. We tested UMM on three visual ERP speller datasets [3] representing 12 (Huebner2017), 13 (Huebner2018) and 54 (Lee2019, 108 sessions) healthy participants. It delivered competitive letter selection accuracy of 92%, 96% and 74%, outperforming the original unsupervised results (Huebner2017, Huebner2018), which is considerable given UMM does not learn over time and never sees more than 68 epochs.

Discussion: UMM is simple, yet effective. Being unsupervised, it neither requires recording labelled nor unlabeled calibration data. As it acts instantaneously on the ERP epochs of the current trial, UMM is immune to non-stationary feature changes over an EEG session. Compared to other unsupervised methods, it can be used for virtually any ERP protocol without requiring changes to the experimental protocol or interface. The proposed instantaneous version of UMM can easily be expanded to consider a history of previous data to obtain improved covariance and mean estimates, which may be useful for more challenging ERP data from patients or auditory protocols.

Significance: Practitioners may want to consider incorporating UMM into their BCI systems to eliminate the need for calibration and to allow participants to instantly use their ERP-BCI application.

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Denoising acoustic-induced vibration artifact in intracranial EEG recordings via a phase-coupling decomposition method

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Introduction: Intracranial electroencephalography (iEEG) recordings offer enhanced characterization in the spatial, temporal, and spectral domains of the neuronal populations supporting cognition, language and speech. Most of the brain-computer interfaces (BCIs) for speech prosthesis are based on iEEG signal decoding. Nevertheless, it has been shown that acoustic-induced vibration artifacts may affect up to 50% of the iEEG channels during recordings of overt-speech tasks [1]. Thus, there is a need to remove acoustic-induced artifacts from iEEG signals. In this work, we present a denoising method - phase coupling decomposition (PCD) - for artifact removal of acoustic-induced vibrations. The artifactual iEEG recordings show a high phase-coupling coherence in the γ-band (70 – 250 Hz) with respect to the produced audio [1]. Thus, PCD seeks statistical components with the highest phase-coupling values with respect to the acoustic signal. Here we validate PCD as a valuable pre-processing tool for speech decoding from neural activity.

Material, Methods and Results: PCD is a data-driven spatial filtering denoising method based on low-rank factorization. Spatio-spectral decomposition (SSD) [2] is first used to enhance signal-to-noise ratio around the γ-band and to reduce dimensionality. Phase-coupling optimization (PCO) [3] is then applied to identify sources phase-locked to the acoustic signal. Data consisted of iEEG recordings from 54 patients performing a syllable triplet repetition task [1]. Data cleaning was assessed based on the percentage of clean electrodes with respect to raw data (% gain). Common average reference (CAR) and independent decomposition analysis (ICA) were applied for comparison. The effect of applying each denoising method (CAR, ICA, PCD) as a pre-processing step in a BCI deep learning model [4] for consonant decoding was also evaluated. Results showed that CAR can increase the number of affected electrodes by spreading the artifact presented in "common noise". Although ICA showed the highest reduction in the number of artifact-affected channels (% gain ICA = 21.4 > % gain PCD = 14.7), consonant decoding performance was reduced due to strong degradation of physiological γ-band modulations.

Discussion: While traditional denoising method can jeopardize signal quality, PCD can significantly reduce the strength and extent of the vibration artifact while preserving the underlying neural activity related to speech.

Significance: PCD is the first method specifically designed to denoise acoustic-induced vibration artifacts in brain recordings and can be safely used as a pre-processing step for iEEG-based speech decoding.

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EMG modulation evoked by classical BCI tasks as a potential control signal for movement augmentation

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Introduction: Spinal motor neurons receive a wide range of input frequencies via the common drive. However, only frequencies below ca. 10 Hz translate directly into motor output. Frequency components above 10 Hz could represent oscillations leaking down from supraspinal sources like motor cortex that do not affect motor output or only indirectly affect movement. Common drive oscillations can be marginally volitionally modulated in the beta band by neurofeedback [1]. We hypothesized that these oscillations can also be modulated by mental tasks classically used in BCI research, as these tasks induce oscillations in cortical areas, potentially leaking downstream. Oscillations of the common drive can be derived from electrical muscle activity and could serve as a control signal in movement augmentation applications. Screening for various discriminable mental tasks could offer here an alternative to a neurofeedback approach.

Methods and Results: We recruited 8 non-disabled subjects between 21 and 47 years. Subjects sat in a chair with their right leg fixated in a foot dynamometer. Subjects executed 336 trials of isometric dorsiflexion with their right foot with 8% of their maximum force. A trial lasted 10s; from 5s to 10s, subjects were asked to perform a mental task additionally. The possible mental tasks were: foot motor imagery (MI), hand MI, mental arithmetic, or rest. We recorded 64 high-density (HD) surface EMG channels from the tibialis anterior muscle, a 1-channel force signal, and 61 electroencephalography channels (the latter was not analyzed here). The reference and ground electrodes were placed on the right and left ankle, respectively. Noisy channels and artefact-contaminated trials were excluded. We calibrated a motor-unit (MU) decoder [2] using HD-EMG data from force ramps recorded at the beginning and end of a session. Subsequently, we used the MU decoder to obtain spike trains of MUs. To get an estimation of the common drive, we superimposed all MU spike trains yielding the cumulative spike train (CST). As an alternative for estimating the common drive, we additionally averaged all HD-EMG channels (avg. EMG). We then applied a filter bank with 4 Hz wide bands between 10 and 60 Hz. Eventually, we classified the four mental tasks from the average power of the frequency bands during mental task execution. We employed a shrinkage linear discriminant analysis classifier. We also classified the force in the time domain to assess possible task-dependent behaviour. The classification accuracies for the subjects are shown in Table 1. Especially, the channel-averaged EMG contained discriminative information and yielded classification accuracies considerably larger than for CST or force for S3, S5 and S8.

Table 1. Classification accuracies in [%] when discriminating the 4 mental tasks based on CST, channel-averaged EMG, or force.

feature type	*S1*	*S2*	***S3***	*S4*	***S5***	*S6*	***S7***	*S8*	***average***
CST	29	23	34	23	39	31	31	23	29
avg. EMG	29	26	**38**	27	**50**	30	**39**	30	34
force	32	31	31	33	32	26	29	24	30
sig. level.	29	29	29	29	29	30	29	29	26

Discussion: We could clearly differentiate the mental task in 3 out of 8 subjects from the channel-averaged HD-EMG. The classification is probably not due to a class-dependent behaviour, as the force signal contains only little discriminative information in relation. Our results also indicate that the channel-averaged HD-EMG contains more discriminative information than the CST, possibly related to the fact that only a fraction of the active MUs can be decoded from surface HD-EMG signals. If the classification accuracies can be further improved by user training, EMG oscillations evoked by mental tasks could serve as a potential control signal for movement augmentation.

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Accurate neuroprosthetic control via neural manifold shaping

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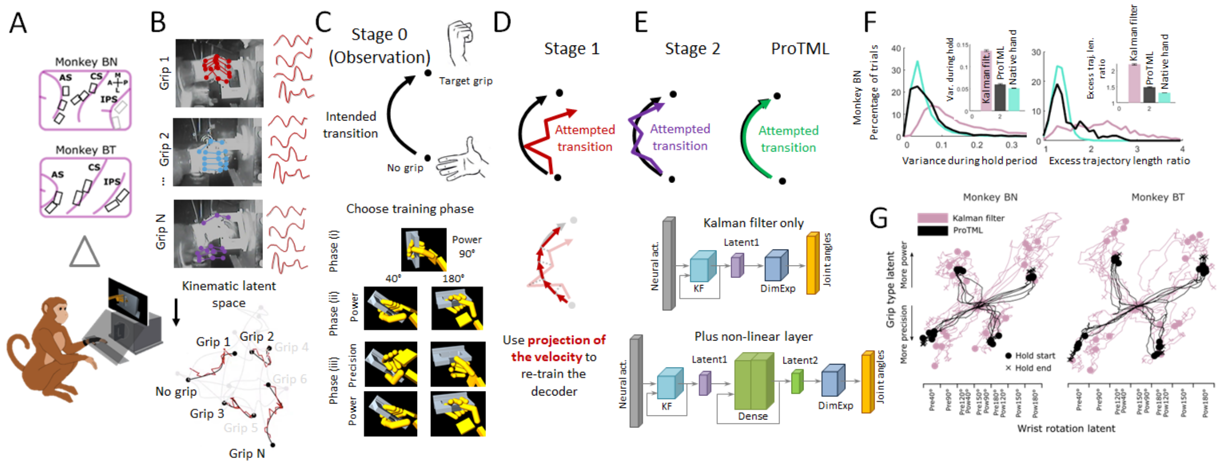
Introduction: Hand movements are an essential way primates interact with the environment and they comprise some of our most complex actions. Despite the remarkable recent progress in intracortical brain-computer interfaces, current prosthesis still lack the fine hand shape control required to interact with objects in daily living. Towards this goal, we present a training protocol to develop the neural activity patterns required for the accurate BCI control of hand shape. The method sculpts neural activity by daily training of objective patterns and enables progressively finer control of hand degrees of freedom, approaching native hand control for some metrics.

Material and Methods: We tested our approach in two rhesus monkeys implanted in key areas of the grasping circuit (Fig. A). Using a high-dimensional full hand and arm tracking system, we determined a subspace of the hand joint kinematics state space we termed the *kinematic latent space* (Fig. B). Based on knowledge of the evolution of neural manifolds [1-5], we trained the subjects to progressively control more latent variables of the hand shape subspace (Fig. C). Building upon intention-estimation training strategies [6-9], our approach takes into account trajectories in the kinematic latent space crucial to achieve final postural configurations. To preserve trajectories and in contrast to previous approaches, we replaced the executed kinematics in the decoder re-training stage with the attempted trajectories (Fig. D). Inspired by machine learning techniques, we trained the subjects with a Kalman filter (KF) but later switched to a hybrid decoder, combining the robustness of the neural patterns developed during KF control with the prediction capacity of a recurrent neural network (Fig. E). We refer to our combined approach as Progressive Training of Manifold Latents (ProTML).

Results: ProTML enables the online control of a high-dimensional hand effector that reflects the grip intention of the subject with accuracy comparable to native grasping. Performance of the BCI was superior to traditional algorithms in several metrics, including success rate and variability of the grasps (Fig. F,G). When compared to a classic intention estimation method in an environment with obstacles, our strategy achieved higher task performance.



Discussion: Our work shows that it is possible to shape neural latent variables to specific target trajectories in the context of motor control. By fitting to a set of target position and velocity targets, daily training evolves these patterns and they can be volitionally recalled by the BCI user. Recent interest on the evolution of neural manifolds in motor cortex has shown that neural patterns are constrained to a covariance space [2], training can expand this space [4], and activity prefers re-mapping to reconfiguration [3]. A protocol for manifold shaping offers an opportunity to observer the evolution and geometry of this latent structure.

Significance: Taken together, these findings propose a novel way to complement training protocols for the challenge of dexterous prosthetic manipulation and offer a training approach to shape neural activity patterns for basic research of cortical activity.

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Improving the performance of non-invasive Brain-Computer interfaces between sessions utilizing Riemannian Procrustes Analysis: Comparison of Deep and Transfer Learning models.

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Introduction: Although brain-computer interfaces (BCIs) show great promise for assisting people in need, BCIs still remain within the laboratory setting due to low classification performance of first-time users and long calibration times required to train algorithms [1]. Brain activity is detected by extracting the relevant brain activity of the participant and then identifying and learning the relevant features by using a machine learning (ML) pipeline [2]. Over the years, deep learning (DL) methods [3] and transfer learning (TL) approaches across participants have been suggested to reduce or even eliminate the long calibration sessions usually required from a participant to control a BCI [4]. Our objective is to compare the performance of DL models and a ML classifier utilizing TL trained across participant's sessions with the purpose of reducing the need for calibration in offline analysis.

Materials and Method: 17 participants were recorded with EEG (32 electrodes) in two sessions. In each session visual feedback was provided to the user while they performed two mental tasks: motor imagery, mental subtractions, with 50 trials per task. Then in an offline analysis two DL models were compared against an ML classifier utilizing Riemannian Procrustes Analysis (RPA) [4] to generalize extracted features across sessions.

Results: Our results suggest that the combination of our best-performing classifier with RPA significantly increases the performance of the system between sessions, within participants.

Discussion: In this study we provide further evidence that matching the statistical distribution of the extracted features between-sessions for each participant could lead to increased performance of the ML pipeline.

Significance: The utilization of TL provides direct evidence on the reduction of the duration of calibration phases and consequently bring the technologies of BCIs a step closer to a more realistic setting and widespread usage.

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Increased spatial resolution reveals separated EEG activation of individual finger movements

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Introduction: The exploration of high EEG electrode densities is of great interest in current BCI research. Therefore, we investigate the neural representations of single-finger movements using high-density EEG.
Methods: The system used in this work is based on flexible electrode grids with an electrode diameter of 5.9 mm and a distance of 8.6 mm between electrode centres [1]. In two healthy subjects, 73 out of 256 electrodes were placed over the sensorimotor cortex contralateral to the hand side of the finger movements. Additionally, nine standard EEG sensors were placed over the same area according to the 10-20 system. All subjects performed voluntary movements of individual fingers. Event-related desynchronization/synchronization (ERD/S) was calculated to produce high-density and 10-20 topography plots [2]. The beta (13-30 Hz) band was used for feature extraction from the EEG. A Wilcoxon signed rank test was used to find significant movement related beta band changes. Fig. 1 shows the topographies, representing superimposed finger activity on the MNI head.

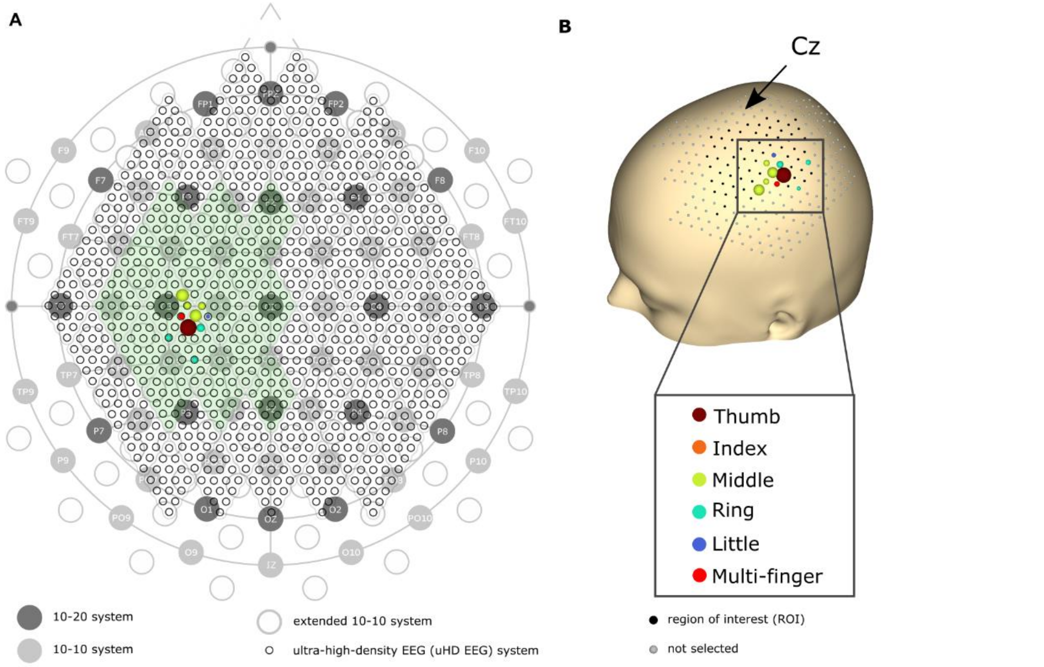

Fig 1: A focal point overlying the sensorimotor cortex around the 10-20 position C3 shows the highest activation. Ten electrodes were color-coded according to the finger with the greatest significance in ERD/S change, one finger includes information from several fingers (Mult-finger).

Results: High-density / 10-20 beta power revealed 11% / 11% single-finger, 1% / 61% multi-finger and 88% / 28% no-finger sites, respectively. Hence, high-density EEG provides more distinguishable features for single finger movement decoding on a smaller area compared to 10-20 EEG recording.

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Single unit recordings reveal high level role of precentral gyrus in speech production

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Introduction: Recently, we showed that intracortical recordings from ventral precentral gyrus (vPCG) can be used to decode speech in real-time at high accuracy [1]. However, the representation of speech at a neural ensemble level has not yet been well described. Here, we show that neural population activity contains a simultaneous representation of up to four syllables of the upcoming word, and that preparatory activity is highly correlated with execution-period activity. These results suggest a higher-level role for vPCG in speech production than previously hypothesized.

Material, Methods, and Results: A Braingate participant with anarthria due to bulbar ALS received two Utah arrays in vPCG. We instructed her to attempt to speak four syllable nonsense words with balanced combinations of phonemes while recording multi-unit threshold crossings from 128 electrodes. We observed phoneme-specific tuning to all four syllables during motor preparation (Fig 1A, blue bars). However, when the syllables were separated into two words, we did not observe phoneme-specific activity for the second word (Fig 1A, orange bars). Additionally, using linear discriminant analysis, we applied phoneme decoders to preparatory and execution related activity and found that they generalized well across contexts (Fig 1B).

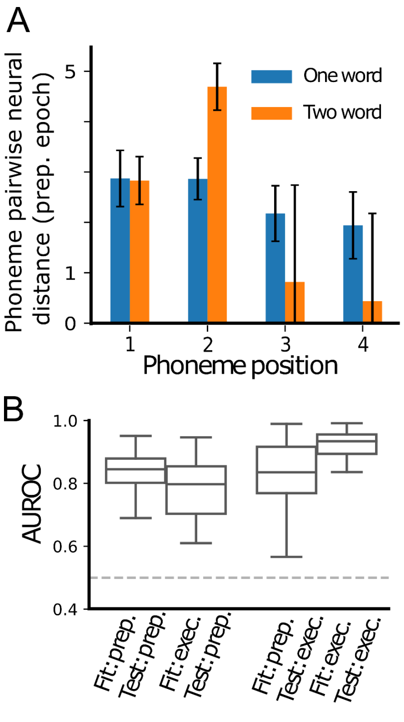

*Figure 1: **A)** Attempted speech of 4 syllable nonsense words has encoding for all syllable postions. When broken into two 2 syllable words, only the first word was encoded. **B)** Decoders fit to preparatory (execution) activity had median crossvalidated AUROC of 0.83 (0.80) for prediction of phonemes during execution (preparation)*

Discussion: We observed that vPCG encodes long sequences of phonemes, but not for more than one word into the future. A low level representation of articulators would predict orthogonal subspaces for preparation and execution as observed in non-human primate dorsal premotor cortex [2]. Instead, vPCG represents phonemes similarly during motor preparation and execution. This suggests that vPCG plays a higher role in the hierarchy of speech production than simply generating the immediately upcoming articulatory motor commands (as predicted by fMRI [3]).

Significance: Further elucidating the role of this region in the speech production hierarchy could facilitate the development of more reliable and faster speech prostheses.

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Optimizing feature selection for word decoding with high-density ECoG

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Introduction: Speech decoding remains one of the key applications of brain-computer interface (BCI)technology in individuals with severe motor paralysis. Latest work has demonstrated successful decoding of phonemes, words and full sentences from high-density electrocorticography (ECoG) brain activity. Undoubtedly, many factors contribute to high accuracy of decoding, yet for the purposes for developing long-term fully implantable BCI devices, in this study, we focus on two factors: 1) the number of intracranial electrodes necessary for obtaining best decoding results, and 2) the location of best performing electrodes on the human cortex. The goal of this study is to optimize the channel selection procedure for high-accuracy word decoding and to identify where best performing electrodes are located.

Methods and Results: Five able-bodied Dutch human participants underwent temporary implantation with 128-channel high-density (1 or 1.2 mm diameter) ECoG grids over the sensorimotor cortex. Each participant performed a word production task, in which they pronounced twelve individual Dutch words ten times. Microphone speech data was obtained simultaneously with high-density ECoG activity, and we ensured that no audio contamination of ECoG data took place. Per subject, using high-gamma component of brain activity (70-170 Hz), we trained a word decoder using a linear support vector machines and a leave-one-out cross-validation scheme. The decoder was set up to prevent overfitting by optimizing its regularization hyperparameter. The resulting accuracy varied considerably across subjects: .83, .73, .63, .87 and .39 (chance is 8%) for subjects S1, S2, S3, S4 and S5, respectively.

For channel selection, we used various versions of recursive feature elimination (RFE) that iteratively dropped one channel at a time based on different signal properties of the channel and the decoder weights. We found that in all subjects, decoding accuracy increased by at least 10% after the channel selection resulting in values of .98, .87, .72, .98 and .60 for S1, S2, S3, S4 and S5, respectively. Per subject, no more than 32 electrodes were needed to achieve this results.

Channel distribution on the cortex varied but appeared to favor electrodes placed over the ventral sensorimotor cortex (face area, both on the motor and somatosensory side). In addition, we explored an alternative channel selection approach with constraints of a smaller grid that is more likely to be used in a long-term BCI implant. For this, we slid a mask of 8x4 electrodes (vertical and horizontal placement) over the full 128-channel (16x8) grid and retrained the decoder on subsets of channels in the mask. The resulting accuracy was somewhat lower compared to the distributed RFE approach: .95, .84, .66, .95 and .54 for S1, S2, S3, S4 and S5, respectively. In all subjects, it covered the ventral sensorimotor cortex (face area). A vertical mask placement that covered inferior dorsal motor cortex was preferred.

Significance: The present study suggests that 1) the use of fewer electrodes may be a powerful way to improve classification results, and 2) both ventral and inferior dorsal parts of sensorimotor cortex may contribute to the best decoding performance. The results of this work will serve as guidance in planning BCI device implantation and positioning of ECoG electrodes for ensuring best speech decoding results. Furthermore, these results improve our understanding of neural signals in relation to decoding for BCI and overall contribute to the discussion about speech motor processing in the brain.

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Offline Prediction of Prolonged Acute Pain by means of Convolutional Neural Network Model applied to Electroencephalographic Oscillatory Connectivity

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Introduction: Unresponsive patients are unable to self-report pain. Hence, the electroencephalogram (EEG) is a potential tool by which caretakers can assess their pain. However, building a pain assessment model always requires labelled data. Since data from unresponsive patients cannot be labelled based on self-report, we aimed to develop a model which can be generalized to novel individuals with no labelled data for training. For this purpose, we trained a convolutional neural network (CNN) model to classify pain and non-pain conditions from EEG signals across individuals.

Material, Methods and Results: Forty-three healthy individuals participated in the experiment (22 females, mean age = 25.36). Due to technical or procedural issues, seven participants' data were excluded and thirty-six participants remained for analysis. There were five conditions involved in the experiment of which we used the pain condition induced by hot water (H) and the resting state with eyes-open (O) for the present analysis.

We segmented the signals into 5-sec trials with an overlap of 50%. As a measure of functional connectivity (FC), inter-site phase clustering (ISPC) was computed within each trial between all pairs of 32 EEG channels [1]. The ISPCs of each trial were reorganized as a 32×32 matrix as the input feature to the CNN model, whose rows and columns represent channels.

The CNN model involves three basic architectures of hidden layers and batch-normalization layers, followed by dropout layers. Fully connected layers and activation functions were applied for classification.

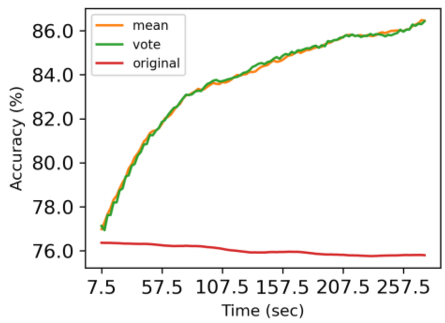

Figure 1. *Mean prediction accuracy versus duration of segment used to accumulate evidence. The model was trained using the data of n-1 participants and evaluated on the remaining 1 participant. This was repeated for all participants.*

We applied leave-one-out (LOO) tests to each participant. In each test, one participant was excluded from the model training and only used in testing, and the model was trained with the other thirty-five participants. Accumulative evidence was computed to evaluate the effect of the number of consecutive trials, where the prediction of one trial depends on the mean prediction score of each class across all trials before the target trial or the most common prediction of single trials before the target.

With every single trial for prediction, the accuracy reached 76.01%±11.72% of binary classification. When accumulative evidence is applied, the maximum level was 87.98%±13.17%. Moreover, mean accuracy reached 80% after 35 seconds.

Discussion & Significance: The individual variation of neural responses to pain obstacles the generalization of the pain assessment model, so models using transfer learning are rare [2]. Recent research suggests that slow alpha frequency correlates with individual pain sensitivity [3]. And that the FC in the alpha band may be an ideal neural marker for pain prediction [1]. Hence, our current attempts showed the potential of alpha FC to reduce the effects of individual differences in pain prediction.

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Early stopping strategies for P300 speller with Bayesian accumulation of Riemannian probabilities

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Introduction: P300-based BCI [1] have been widely investigated; it provides a resourceful ground to build BCI speller applications, as proves the numerous many experimental or commercial frameworks. Most of the P300 speller literature focus on the detection of P300, with the objective to reach single trial classification, while existing frameworks still require several repetitions to yield proper accuracy.

Unlike previous works, Bayesian accumulation of Riemannian probabilities (ASAP) [2] considers the full problem of character classification based on P300 detection, providing an end-to-end machine learning pipeline, from feature extraction at signal level to character selection at user-interface level by Bayesian accumulation. This seamless processing of information from signal to BCI characters outperforms standard methods [2]. However, ASAP does not describe *when* a character could be selected before moving to the next one. This work tests different strategies for early/dynamic stopping.

Material, Methods and Results: Existing literature proposes to increase the confidence of characters solely when they are flashed, following a *maximization of occurrences* (OM). ASAP relies on Bayesian accumulation to update the confidence of each character after each flash. The comparison between Bayesian accumulation and maximization of occurrences is illustrated on Fig. 1-left. We investigate here the role of early stopping to make the most out ASAP model (Fig. 1-right) using Timeflux[1].

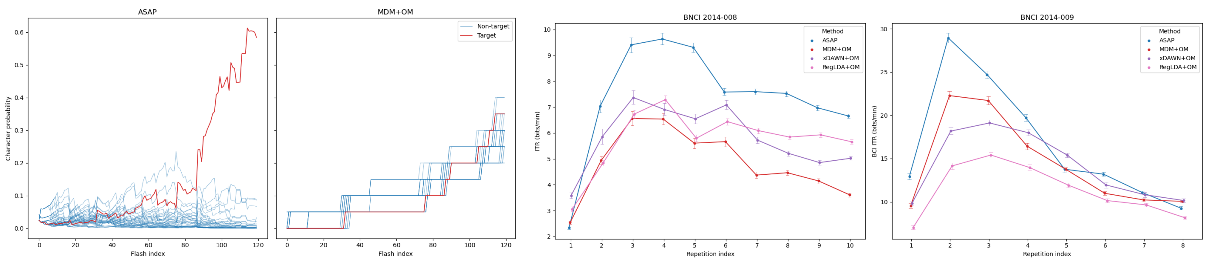

Figure 1: Left: Character probabilities as a function of flash (target character in red, non-target characters in blue) on ASAP (left) and Riemannian Minimum Distance to Mean (MDM+OM, right). Right: BCI ITR (in bits/min) as a function of repetition, for ASAP and state-of-the-art classifiers.

Discussion: Different strategies allow balancing the prediction accuracy with the ITR. ASAP provides a solid ground to investigate the different early stopping strategies, with rich information as the probabilities of all characters are available anytime.

Significance: This work provides a fast P300 BCI, and aims to bridge the gap between published literature on offline dataset and usable interface for empowering people.

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Comparison of BCI headsets for at-home use by children with complex needs

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Introduction: Access to simple BCI systems at-home are increasingly showing positive impact for children with complex physical disability [1]–[3]. However, current headset design does not target children or the home and there is pressing need to evaluate BCI headsets for children capable of advanced BCI control paradigms. This work aims to compare candidate headsets across several metrics: signal quality, ergonomic design, cost, and usability to identify strengths and drawbacks that may affect at-home BCI use by children and families.

Materials, methods and Results: Candidate headsets were selected based on feedback from children, families, clinicians, and BCI experts in the clinical BCI4Kids program [3]. Primary inclusion properties were to be wireless, dry (or gel-free), and require limited set-up. Headsets were evaluated by BCI experts (n=5) on EEG quality, and self-reported measures of tolerance (1-10; unnoticeable to unbearable) and aesthetics (1-10; unappealing to very pleasing) EEG was recorded under 3 conditions: at-rest, intentional artifact induction (head rolling), and attending to a visual stimulus (steady-state LED flashing at 10 Hz). Resting EEG quality was evaluated using the EEG quality index (EQI) [4] compared to a gel-based standard BCI headset serving as a control A modified signal-to-noise ratio (SNR) was computed for occipital electrodes (Pz/O1/O2 as available) during the visual stimulus trials against control the headset.

EQI of resting-state EEG revealed large per-subject variance across headsets (Fig 1.A), with a trend revealing HS3 and HS5 performing lowest across channels and metrics. All headsets showed positive SNR amplitudes (Fig. 1.B) in response to the visual stimulus. However, headset 5 again had a smaller SNR compared to the rest. HS3 was unanimously the most comfortable (1.17 ± 0.41) and the most aesthetically pleasing (7.00 ± 1.55).

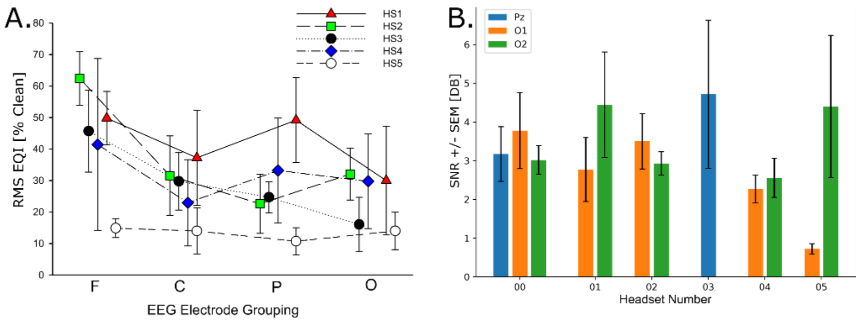

Fig. 1. A) Root Mean Squared (RMS) EQI Metric for resting data for electrodes in similar locations: F = Frontal, C = Central, P = Parietal, O = Occipital. B) SNR of all headsets including the gel-based standard control (headset 00).

Discussion: No single headset from the candidates stood out as the best option across all lines of investigation. The high variance in EEG quality across channel regions and metrics emphasizes there may not be a one-type-fits-all headset. More personalized evaluation of potential systems should be employed for at-home use by children with end-users engaged to identify the optimal systems for real-world BCI use.

Significance: Candidate headsets with potential for at-home use by children with physical needs have variable strengths and weaknesses in their EEG quality, comfort, and aesthetics.

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Advancing artifact handling in BCI research: from filtering to non-neuronal artifacts

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*Introduction***:** Research studies relying on electroencephalography (EEG) require some handling of non-neuronal data to function with sufficient data resolution for interpretation. For non-implantable BCIs, this requirement becomes even more important as the underlying potentials used for classification are now real-time instead of averaged data, and every inquiry into a user's state costs time. Furthermore, each BCI system operates under different working assumptions. For instance, a blink may constitute an artifact or an enhancer of classification performance in P300 spellers, depending on the time and consistency of the response [1]. The data may not be recoverable under certain circumstances due to presence of artifacts or a user's inability to perceive a target stimulus, and it may be necessary to recollect data in real-time (ask again; retry) as opposed to undergoing costly signal reconstructions and attempting to make inferences with it. Therefore, bridging the gap between customary neurophysiological methods of artifact handling requires nuance and a systematic understanding of the operating limits of the BCI system utilized [2, 3]

*Methods, Materials, and Results***:** In this study, we leveraged rapid serial visual presentation (RSVP) calibration data collected for a pilot study of thirty-one non-disabled participants (age 49.4 ± 19.99 years). EEG data were collected using a DSI-24 cap (Wearable Sensing) at a sampling rate of 300 Hz. RSVP calibration occurred with letters presented at a rate of 5 Hz, for 110 inquiries of ten letters (resulting in 1100 total trials for calibration) using BciPy [4]. Two neurophysiology researchers labelled the data for the following artifact types: peak voltage, blink, EOG, EMG, ECG, flat voltage, and event (unknown origin, but non-neuronal, such as movement). Two filtering pipelines were tested on the calibration data: 1) conventional training, where the whole dataset was filtered, then epoched into trials for training, and 2) inquiry-based training, where the data were epoched as it would be in real-time, filtered, then epoched again into trials for training. A bandpass filter of 1-20Hz, order 2, 60Hz notch was used. In addition to this question, we trained our models on data conventionally filtered with all prelabeled artifacts described above removed. Trained models from calibrations were generated in BciPy using PCA pre-processing and a regularized discriminant analysis [4]. Using a paired t-test, the inquiry-based filtering approach ($M = .782$, $SD = .015$) worked significantly better for classification (AUC) than the conventional filtering ($M = .768$, $SD =.014$) ($t(30) = 3.34$, $p < 0.002$). Removing all artifacts ($M = 210$ epochs with artifact dropped) resulted in no meaningful change in classification performance (AUC) in this population ($p < 0.1$) using a conventionally filtered dataset.

*Discussion***:** Artifact rejection in BCI systems remains a challenge. Our data suggest that upfront categorization of signals and noise per paradigm may benefit the overall system, as a one--fits-all-approach to artifact seems unlikely across BCIs [1, 2, 3]. Future studies should attempt training on subsets of specific noise types as described above and add simulated and/or real typing data to see how these models perform when encountering real-time data with artifacts. This will be necessary to deduce how each type, with varying amplitudes and morphologies and time relationships to targets/non-targets, will impact classifier performance. A limitation of this study was that additional samples could not be collected after artifact removal, and the use of fewer training samples may have its own cost, particularly when concerning the target trials, which are much less frequent (<=100) vs. nontargets (<=1000). Furthermore, while preliminary data suggest that removing all non-neuronal signals may not result in a significant classifier improvement, it may still be better to continue without the artifacts depending on the research question and the temporal proximity of artifacts to the signals of interest.

Significance: Artifact detection and handling are fundamental components of a functional BCI system. These procedures can cause a benefit or detriment. We describe an approach and considerations to improve this discourse.

Acknowledgements: This work was supported by NIH R01DC009834.

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Long-term effect on EEG sensorimotor responsiveness to motor imagery after a BCI training for stroke rehabilitation

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Introduction: Previous studies demonstrated the efficacy of EEG-Brain-Computer Interfaces based on Motor Imagery (MI-BCI) in post-stroke functional motor recovery of upper limbs [1]; however, the maintenance of such effects in the long-term is still partially unexplored. Here we tackled this long-term aspect of MI-BCI induced positive effects on rehabilitation outcomes by analyzing an EEG dataset acquired from subacute stroke patients recruited in the longitudinal Randomized Controlled Trial reported in [2]. The oscillatory activity in the EEG beta band known as related to MI tasks within BCI contexts [1], [3], was studied at different time points in two groups of participants one performing MI practice with BCI assistance (BCI group) while the other performing MI training alone (CTRLgroup).

Material, Methods and Results: EEG data of 17 patients (8/9, BCI/CTRL), performing MI of grasping and finger extension with their affected hand (same tasks employed in the intervention training), were analyzed. The 61 EEG channels were 1-45 Hz bandpass filtered. After artifacts rejection data were segmented in task (N=20±1) vs rest (N=20±1) 4s-trials. Then the Common Average Reference was applied. Power spectral density (PSD) was computed following Welch's method with a 0.3 Hz resolution and 1s Hamming window. Averaged beta PSD in task vs rest condition was compared between participants, in both groups separately, with a 2 tailed-paired t-test pre- (T0) and post-training (T1) and after 1, 3 and 6 months (T2, T3 and T4). The t-values obtained are plotted in Figure 1. In the BCI group at T1, the activation focuses on sensorimotor channels bilaterally with a greater involvement of the healthy hemisphere which wanes from T2 to T4 maintaining a more physiological topography with a balance between the hemispheres. In the CTRL group, a diffuse activation is visible with no apparent temporal evolution. As expected, both groups improved upper limb motor function as assessed by Fugl-Meyer Assessment (FMA) (tab.1).

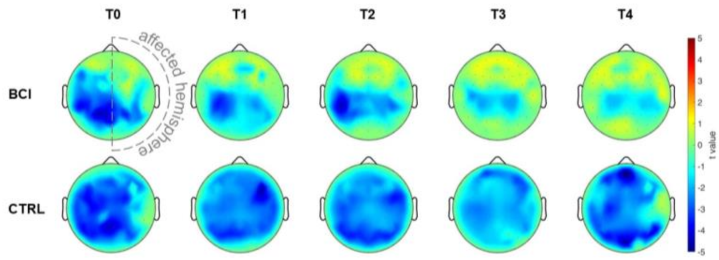

Table 1 *Average (±Standard Error) of the Fugl-Meyer Assessment (FMA) before (T0) and after (T1) the treatment for BCI/CTRL groups.*

	FMA(T0)	FMA(T1)
BCI	14.8 ± 5.9	27.4± 6.9
CTRL	19.4 ± 4.7	32.6± 7.8

Figure 1. *t-values distributions obtained from the comparison in the beta band of task and rest conditions at timepoints T0, T1, T2, T3, T4 for the BCI group (first row) and for the CTRL group (second row). The affected hemisphere is the right one for all as the channels flipping was applied for those patients with left affected hemisphere. Data of grasping and finger extension imagination were pooled.*

Discussion: Our results suggest that MI-BCI modifies EEG reactivity to the MI task. We impute this modification to the effect of MI training in a closed-loop, which results in a more uniform behavior among patients in the BCI group.

Significance: This preliminary study reveals long-term effects of MI-BCI on sensorimotor EEG reactivity. Furthermore, the rebalancing of activity between the hemispheres suggests brain plasticity changes whose relationship with functional recovery will be investigated in future studies.

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EEG-SimpleConv, an efficient and fast architecture for Motor Imagery EEG classification

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Recent studies in EEG decoding have shown that deep learning methods have good classification performances, without the need for *ad hoc* preprocessing techniques and feature engineering steps in the design of Brain-Computer Interface (BCI) classifiers. Nevertheless, deep-learning methods in motor imagery (MI) tasks stagnate in offering high accuracies, suffer in some cases from biased evaluation of model performance, and are usually tested on single datasets. This limitation can be associated with the fact that the proposed models fail to generalize to different EEG recording systems and setups. In addition, the rationale behind specific architectural or optimization choices is often unclear and scarcely validated.

We propose EEG-SimpleConv, a straightforward convolutional neural network with a regular architecture. We evaluate its performances on three EEG MI datasets (BCI IV-2a[1], Physionet MI[2], and Cho 17[3]) and compare it to recent deep learning models (EEGNetv4[4] ,TIDNet[5], EEG-ITNet[6]). We test different optimization techniques such as Mixup, Euclidean Alignment (EA), and batch normalization on the test set statistics, and evaluate their impact on classification performances with an ablation study. EEG-SimpleConv shows up to 6% improvement in accuracy in different scenarios and datasets compared to the other models. In fact, this model shows a trade off of high number of parameters that enables better learning, and a low inference time which explains how fast the proposed model is. We have also made Our code freely accessible at `https://github.com/GhBlg/EEG-Benchmarking`.

Keywords : Electroencephalography (EEG), Brain-computer interface (BCI), Motor Imagery (MI), Deep learning (DL), EEG Classification

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Table 1: model performances across datasets (standard deviation).

		EEGNet	TIDNet	EEG-ITNet	EEG-SimpleConv
Datasets	BCI IV-2a	70.31 (8.09)	63.52 (6.38)	69.83 (7.58)	**76.26 (7.73)**
	Physionet MI	65.94 (2.94)	58.94 (2.37)	65.73 (3.14)	**69.27 (2.09)**
	Cho 2017	70.88 (6.37)	67.35 (4.91)	71.18 (5.57)	**77.93 (3.96)**

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Assessing the Potential of VASO-fMRI to Determine which Cortical Layer Offers the Best Motor Decodability for ECoG BCI

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Introduction: Functional Magnetic Resonance Imaging (fMRI) is frequently used to establish the feasibility and optimal location for a Brain-Computer Interface (BCI) [1]. While standard fMRI provides information for the placement of BCI implants, it does not distinguish between cortical layers. Knowing which layer provides optimal decoding information affects the optimal electrode size [2]. However, the blood oxygenation level-dependent (BOLD) signal, generally used for fMRI measures, includes a strong contribution from draining veins making it less spatially bound to the locus of neuronal activity. Vascular-Space-Occupancy (VASO) fMRI is specifically sensitive to changes in blood volume, which are spatially more tightly linked to the electrophysiological sources [3]. In this study, we establish the potential of using VASO to determine the optimal cortical depth for decoding movement for implantable BCIs, thus aiming to optimise the electrodes' location and their optimal size.

Material, Methods and Results: High-resolution VASO/BOLD data (0.85x0.85x1.5 mm) were acquired in three subjects on a 7-Tesla scanner using a 32-channel surface coil over the left sensorimotor cortex. Subjects performed two gestures from the American Sign Language with their left and right hand in a slow event-related design. Data were preprocessed using SPM12, custom MATLAB scripts and LayNii tools [4]. Support vector machines (SVMs) were trained to distinguish gestures based on either ipsilateral or contralateral activity. Decoding results indicated that while VASO could distinguish between gestures of the contralateral hand (μ=64%), classification based on ipsilateral activity was close to chance (μ=56%). Classification accuracy was reduced relative to BOLD classification, with BOLD being able to classify based on contralateral (μ=87%) and ipsilateral activity (μ=78%). First results for the layer-specific activity profiles confirm that VASO is spatially more linked to the neuronal sources, while the BOLD signal is amplified in the superficial layers (Fig. 1).

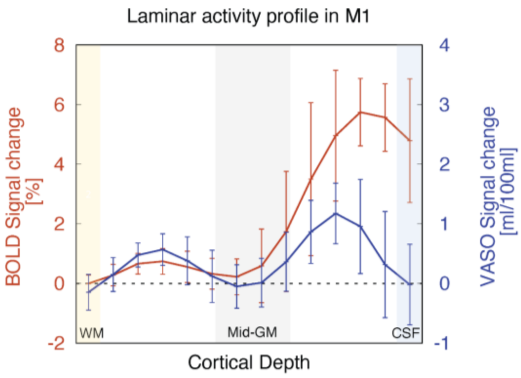

Figure 1*. Signal changes (mean and standard deviation) across cortical depth during contralateral hand movement (n=1). The cortical depth is approximated; measurement points do not correspond to biological layers.*

Discussion and Significance: Our results show that VASO has the potential to be used for assessing the feasibility of BCI designs, thereby providing a means to locate the necessary differential neuronal sources more precisely. As the signal-to-noise ratios of VASO are reduced relative to BOLD, it would benefit from more trials and, thus, longer measurement periods to train SVMs adequately. Future research will include the assessment of layer-specific classification, which can help to assess the nature of the neuronal sources driving a BCI more precisely.

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Tracking variability in subject state and iBCI performance over time

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Introduction: Intracortical brain-computer interfaces (iBCIs) allow individuals with motor impairments to directly control effectors like computer cursors by decoding patterns of neural activity that can be used to control effector kinematics. Fundamental to the iBCI is the mapping between neural activity and intended kinematics. However, non-stationarities in the neural data alter this mapping over time and therefore reduce iBCI performance [1]. It is thought that changes in subject state, such as fatigue or pain, contribute to these non-stationarities. Therefore, accounting for these state changes could allow for more robust implementation, for instance by updating a decoder [2] based on a reference dataset collected when the subject previously had been in a similar state. Here we report an interim analysis of the relationship between subject state (e.g. pain or fatigue) and iBCI performance.

Material, Methods, and Results: As part of an ongoing study, we recorded intracortical activity from the motor cortex of two participants with tetraplegia using intracortical microelectrode arrays (Blackrock Microsystems, Inc., Salt Lake City, UT). Participants completed BCI-controlled cursor tasks in lab and home environments. During each session, the participant completed a structured task, which was a gamified 2D center-out task featuring both translation and click [3]. Subjective ratings of pain, fatigue, and sleep quality on a 0-10 scale were recorded before each session. Seventeen days of data were collected from participant P2 and 5 days from participant P3. Figure 1a shows that both participants experienced pain and fatigue, as well as less than optimal sleep, on all days of testing with more variability for P3. Figure 1b shows that while success rates were generally high, they varied from day to day for both participants. Higher fatigue was inversely correlated with success rate in P3 ($r = -0.94$, $p = 0.018$) while no other state variables were predictive of performance in either subject.

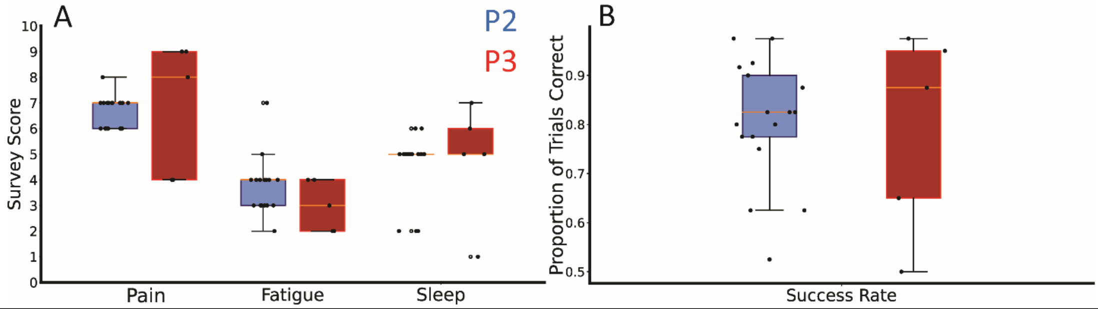

Figure 1 – Distribution of subject state survey scores and iBCI success rate. A. Participants indicated perceived pain level (0=no pain, 10=worst pain imaginable), fatigue (0=no fatigue, 10=most fatigue imaginable), and sleep quality (0=worst sleep imaginable, 10=best sleep imaginable). B. Fraction of trials (typically 40 total) completed correctly in the click-and-drag task [3].

Discussion: The participants experienced variability in both subject state and BCI performance despite both having multiple years of experience; 7.5 years for P2 and 2.5 years for P3. There was a relationship between fatigue in one participant and performance, but these basic survey metrics were not able to explain all the variability seen across days in performance. Pupillometry data is being collected from both participants that may yield greater insight into subject state and task engagement [4].

Significance: We observed day-to-day variability in both subject state and performance metrics across two participants with significant BCI experience. Improvements to iBCI design to make them more robust to this variability could promote wider clinical adoption.

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Using General-Purpose Meta-Learning Algorithms to Train a BCI Classifier on Less Data

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Introduction: Meta-learning enables using the prior experience of the neural network from previously learned tasks to improve performance on a new task. In BCI-related applications this means the ability to use data from previous users to reduce the amount of data needed to train on new users as well as improve the quality of classification. An important advantage of *MAML* [1] and *Reptile* [2] meta-learning algorithms is that they can be easily applied to most neural networks based on gradient descent. In comparison with the classical pre-training, these algorithms allow better optimization of the starting weights for training on a new task, and also better generalize the starting weights on the training set of tasks [1].

Methods: We used the *EEGNet* [3] as the classifier and *MAML* [1] and *Reptile* [2] as meta-learning algorithms. The classifier was separately applied to the EEG data from 13 participants recorded in study [4], where two classes of 19-channel EEG epochs were collected: related to intentional eye fixations used to make actions in a gaze-controlled game and related to unintentional, spontaneous fixations. A meta-*EEGNet* model was trained using a meta-learning algorithm on the data of all participants except one which we call the test participant. In the tuning phase the model was trained on 50% of the test participant data and finally tested on another 50%. The baseline *EEGNet* was trained on 80% of the data of this participant and tested on another 20%.

Results: Group averaged ROC AUC was 0.70±0.10 (M±SD) for the baseline *EEGNet*, 0.75±0.09 for the *MAML-EEGNet* and 0.69±0.07 for the *Reptile-EEGNet*. The difference was not significant, according to Wilcoxon signed rank test (p = 0.17 and p = 0.41, respectively).

Discussion: With prior meta-learning, training on 50% of participant's data enabled comparable or better classification performance relative to the basic classification algorithm trained on a larger subset, i.e., on 80% of data.

Significance: The results provide initial evidence for the effectiveness of the *Reptile* and *MAML* meta-learning algorithms in training a BCI classifier for new users. As these algorithms can be easily applied to a wide range of neural network classifiers, they may appear as prospective tools for reducing the amount of training data that need to be obtained in a new user to achieve a reasonable performance.

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An online tool to facilitate the assessment of BCI acceptability

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Introduction: The acceptability of a technology corresponds to the explicit willingness of potential users to use said technology before having tried it [1]. Assessing the acceptability of new technologies provides valuable insights regarding people's expectations and how to favour technology adoption. Our systematic review of the literature reveals that only four articles report assessments of BCI or neurofeedback (NF) acceptability that are based on validated questionnaire or model [2]. We hypothesise that the lack of studies on this subject is, at least in part, due to the absence of acceptability models and questionnaires that are specific to BCIs/NF. Thus, we propose an online tool - https://bci-acceptability-tool.cnrs.fr/ - (see Fig. 1) that aims at providing BCI and NF researchers with an adapted questionnaire to evaluate the acceptability of their device.

Material, Methods and Results: We based our tool on the 3rd version of the technology acceptance model [3] and the 2nd version of the unified theory of acceptance and use of technology [4] as they are the most widespread and result from many studies on different technologies. As those models are generic, they do not enable accounting for all the determinants of BCI acceptability. Therefore, we designed a new model including new determinants that should be considered to assess BCI acceptability, e.g., temporal behavioral intention takes into account the duration of the BCI use. This model is very detailed in order to be applicable to the majority of contexts of BCI use. Nevertheless, it is flexible and adapted to different use cases. Indeed, based on the answers provided by the users on the online form, the tool enables them to download a questionnaire that is context adapted.

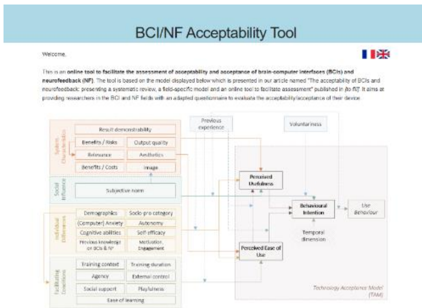

Figure 1. *Screenshot of our online tool.*

Discussion: The model developed has been validated and specified for post-stroke motor rehabilitation through a large-scale study involving 753 persons without motor disabilities [5]. We plan to improve the tool by adapting the factors to assess depending on each context of use with the results of future acceptability studies, which it will foster and allow carrying out in a reproducible and reliable manner.

Significance: Using the free, online tool that we propose, researchers can download a BCI-oriented acceptability questionnaire adapted to their context of use.

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Decoding speech intent from non-frontal cortical areas

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Introduction: BCIs aiming to decode speech production to restore communication have largely recorded signals from the speech sensorimotor cortices, including ventral pre-central and postcentral gyri and inferior frontal gyrus [1-3]. The temporal and the parietal lobes are important areas of interest for speech and language perception, but thus far there is a lack of evidence of a speech production signal in these areas. If we could decode speech production from these areas, it could potentially be used to restore communication to people with communication disorders, including expressive aphasia, in which the frontal lobe is damaged. Here, we sought evidence for a speech production signal using electrocorticographic (ECoG) signals recorded from the temporal and parietal cortices from 4 participants.

Materials, Methods, and Results: ECoG arrays containing 19 to 64 electrodes were placed on the temporal and/or parietal cortices in participants undergoing resection of epileptic foci or brain tumors. In participants with epilepsy, standard arrays (10-mm interelectrode spacing) were placed according to clinical necessity. In participants with tumors, mini-ECoG arrays (8x8, 4-mm interelectrode spacing) were placed on the temporal and/or parietal lobes intraoperatively. Participants were presented with single words on a screen in random order. They were instructed to read each word silently, hold it in memory while viewing a blank screen, and then cued visually to say it out loud. This enabled us to disentangle the ECoG signatures of speech production from those of reading or comprehension. ECoG high-gamma (HG) band [70-300 Hz] power in 100-ms non-overlapping windows was used as features for decoding speech intent. Each window was labeled according to the respective behavioral state: speech or silence. To avoid bias due to imbalanced classes and only include causal information, for every spoken word we included either a speech window at the voice onset of that word or a silence window from 1.5-1.6 s after the voice offset of the word. We trained a linear support vector machine to classify the behavioral state of each window using a history of 4 windows. We varied the offset between HG power and speech/silence window from -1.5 s to 0.7 s, where negative values indicate HG leading behavior.

Using this technique, we decoded speech vs. silence, using only causal information (last HG bin before speech/silence window onset) with accuracies ranging from 67.2%-80% over participants ($p<0.03$ in all participants, t-test, compared to shuffled labels). To further investigate evidence for a speech intent signal, we used demixed principal components analysis on the HG power from these cortices. We computed the principal components using HG data from -0.5 s to the onset of speech. We observed a separation between the speech and silence behavioral states in a lower dimensional space using the first 2 most significant demixed principal components.

Discussion and Significance: These results suggest that there is a speech production signal encoded within the temporal and parietal lobes. This signal appears approximately 500 ms prior to the onset of intended speech and can be seen in a low-dimensional manifold of HG power as suggested by demixed PCA. The existence of such activity in the posterior superior temporal lobe has been suggested in some linguistic speech production models, but there has been limited evidence for this activity to date [4]. These results inform us about previously understudied cortical areas for spoken language production. This may advance the development of speech BCIs for people with communication disorders including language disorders (aphasia) as well as motor speech disorders (locked-in syndrome).

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EEG-based quantitative measures to support the clinical prognosis of disorders of consciousness

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Introduction: People who survive a severe brain injury can suffer from disorders of consciousness (DoC), a clinical condition characterized by alteration in arousal and awareness that leads to states defined as MCS (Minimally Conscious State) or UWS (Unresponsive Wakefulness State). The process of exiting from DoC is still not clear and it is important to identify markers in bio-signals to predict patients' prognosis with a high accuracy level [1].

Material, Methods and Results: The study involved 58 subjects clinically diagnosed as DoC (40 MCS, 18 UWS) whose clinical condition was followed-up after three months (T_1). Patients were divided in two groups according to the assessment at T_1: 28 positive (O+) and 30 negative outcomes (O-). O+ patients exited the disorder at T_1 recovering communication with the external environment, while O- either didn't change their state or passed from UWS diagnosis to MCS diagnosis or vice versa or died. At study entry EEG signals (19 electrodes according to 10-20 system) were acquired during 5 minutes of resting state. Partial Directed Coherence (PDC) was used to estimate functional resting state network [2] and complex connectivity measures were evaluated according to graph theoretical approach [2]. A statistical analysis was then applied to find indices significantly different between O+ and O-. We found higher values for O+ in comparison with O- for: left-right (LR) influence in delta, theta and alpha bands, inter-hemispheric connections (IHC) in delta and alpha bands, antero-posterior right (APR) connections in delta and theta bands (Fig. 1, panel a). The combination of the significant three indices evaluated in the different bands was used to train a SVM classifier aimed at predicting patients' prognosis. The features that obtained the best classification performance (i.e., accuracy: 85%, AUC: 85%) were: APR connections and IHC in delta band and LR influence in alpha band (Fig. 1, panel b).

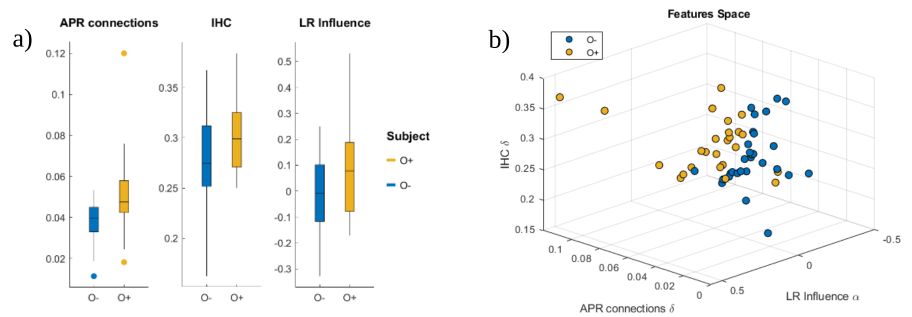

***Figure 1.** a) Boxplot reporting indices distribution obtained for O+ and O- patients; panel b) features space used to classify O+ from O- patients.*

Discussion: The re-emergence of connectivity patterns has been already demonstrated to be an indicator of recovery of consciousness, especially fronto-parietal connections [4]. In the present study, this result is supplied by the additional information of the direction of the connections and the pertinent hemisphere.

Significance: The present study predicts with high accuracy the process of consciousness recovery relying just on quantitative connectivity indices calculated with advanced techniques from EEG signal acquired at resting state.

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Cross-dataset Few-Shot Learning for Motor Imagery BCI classification

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Although promising for many applications, current BCI systems still suffer from several limitations. Indeed, there is a gap between the performances obtained in laboratories and those obtained in practical use. In general, to reduce this gap, a long calibration to adapt the device to a new user is required. This makes BCI democratization in real applications difficult. Several works have focused on this problem proposing various type of approaches. However, the cases treated often lack realism compared to real applications (e.g. the test dataset has a recording setup close to the training data and/or the method relies on unlabeled data collected from the test subject). Moreover, there is currently very little work on cross-dataset transfer learning. To address this gap, the NeurIPSBEETL Challenge [1] has recently proposed a framework to evaluate transfer learning algorithms on both unseen subjects and datasets. We believe that this is a very good starting point to evaluate EEG signal classification algorithms in close to real life conditions. For this purpose, we rely on an experimental framework similar to the BEETL Challenge, with additionally simulating an even more restricted access to data.

On the other hand, low data regimes are not specific to BCI systems, and the field of Few-Shot Learning (FSL) has emerged to deal with these settings. The work in this field aims at classifying a large amount of unannotated data, by training a model on a few annotated examples. In our work, we propose to build on recent advances in FSL to establish an efficient model for cross-dataset MI classification. Based on an efficient Neural Network architecture, that leverages simple 1d convolutions layers, and using standard FSL training routines, we train a robust Deep Learning backbone on a large set of different datasets. This backbone is then used to extract relevant features to perform EEG signal classification, in setups with very few shots (e.g. 1/5/10/20, n-shot meaning that we have n labeled trials per class).

We evaluate the efficiency of our method by comparing it to standard transfer baselines (e.g. Fine-Tuning the backbone on few data of the new subject), as well as non Deep-Learning based baselines. We evaluate its robustness by experimenting on several open-source datasets. Some preliminary results are shown in Fig. 1.

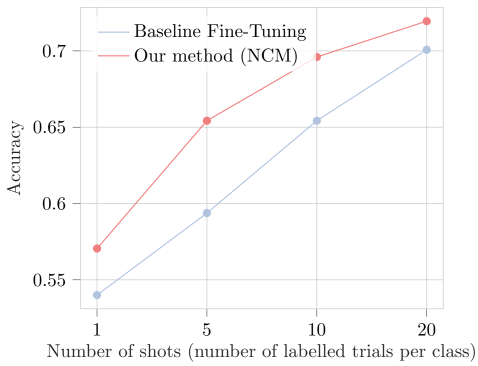

Figure 1: *Preliminary results, using a the BEETL Challenge setup, with Zhou2016 [2] as target dataset.*

Experimental results showed that our method can significantly reduce the amount of training data required to achieve a given level of performance. We believe that our work will help designing BCI systems quickly adaptable to a new user, for any given EEG recording setup.

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A Model-based Dynamic Stopping Method for c-VEP BCI

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Introduction: Brain-computer interfaces (BCIs) are becoming a reality and passes the borders of being only used for assistive technology. To increase the speed of BCIs, dynamic stopping methods [1] at any timepoint make a decision to eject a symbol or wait for more information, based on the decoder reaching a certain confidence. Thus, a speedup can be achieved by exploiting variance between trials, (good trials are detected earlier) while overall adequate accuracy is obtained without a drastic extension of the selection time. However, optimizing measures such as symbol per minute (SPM) and information transfer rate (ITR), do not necessarily reflect the performance of the system for a certain application or certain type of user. For example, for a brain-controlled alarm signal, while high accuracy is essential, it may be vital to have a low miss rate. This shows the need for dynamic stopping methods that can assign different costs to each type of error (false alarms and misses) and minimize cost instead of error rate.

Material, Methods and Results: We propose a model-based approach that takes advantage of the analytical knowledge that we have about the underlying classifier model. We can analytically show that the similarity score between the observed and predicted response, for both target and non-target classes, follows Gaussian distributions. We have formulated the dynamic stopping paradigm as a binary hypothesis decision problem with the following hypotheses:

H_1: observed score F_y is drawn from the distribution of the target class $N(\alpha b_1, \Sigma_1)$
H_0: observed score F_y is drawn from the distribution of the non-target class $N(\alpha b_0, \Sigma_0)$

We can assign different costs to different courses of action, namely: C_{00}: the cost of choosing 0 while 0 is true (Correct Rejection), C_{01}: the cost of choosing 0 while 1 is true (Miss), C_{10}: the cost of choosing 1 while 0 is true (False Alarm), C_{11}: the cost of choosing 1 while 1 is true (Hit). We define the cost ratio as $CR= C_{10}/C_{01}$ and calculate the risk (R) as the sum of costs weighted by the likelihood of each course of action. We then use a likelihood ratio test based on Bayes criterion to find the decision region in which on average R is as small as possible [2]. Using this formulation, we can tune the dynamic stopping algorithm to aim for minimizing the total risk. Additionally, we can set target values for the probability of False Alarm (p_f) and the probability of a Miss (p_m). We have tested the proposed dynamic stopping method on the c-VEP data set provided by [3]. Our preliminary results show that by only using a small cost ratio, the system tends to be very fast (average time $\bar{t}$=318*ms* for CR=1) and inaccurate (error rate Err=81.9% for a 36-class problem). Increasing the cost ratio to $CR=10^6$, resulted in $\bar{t}$=2.32 seconds and Err=22.9%. By adding constraints on the probability of false alarm (p_f=0.05) and determining a minimum probability of detection ($p_d=1-p_m=0.8$), the system withholds making decision, resulting in $\bar{t}$=1s and Err=45.8% for CR=1 and $\bar{t}$=3.4s and Err=15.9% for $CR=10^6$.

Discussion: Using the model-based dynamic stopping approach based on signal detection theory, a BCI system can be tuned to achieve desired performance in terms of False Alarm and Miss rates. Our results show that minimizing risk can result in a very fast detection rate that can be useful in applications where the relatively low accuracy can later be compensated by post-processing, for example, employing a language model. Imposing a target probability of false alarm and a minimum detection rate makes it possible to tune the system for more error-sensitive applications.

Significance: Our proposed model-based dynamic stopping algorithm allows for tuning the BCI systems according to the requirements of each application.

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Detecting Threat Detection

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Introduction: The understandable importance of detecting threats in real-world situations is evidenced by the prioritization of attention allocation to threat stimuli [1]. The findings presented here represent the first phase of an extensive study investigating the capacity of a neuroadaptive technology to provide an advantage to the human user in threat environments. This phase one study aimed to identify early neural correlates of threat detection, measured via electroencephalography (EEG) in a controlled experimental paradigm, to determine the level of accuracy of threat detection that is achievable on a single trial basis, when compared against non-threat and distractor stimuli.

Material, Methods and Results: A rapid-serial visual presentation (RSVP) task [2], [3] (N = 28) was used to elicit a brain response to stimuli that were either threatening, novel (distractors), or non-threatening (referred to as stimulus type), with stimulus presentation rates of 100-175ms, 200-275ms, and 300-375ms. The EEG data were epoched and standard machine learning methods were used for feature extraction, calibration and testing. For each stimulus type and presentation rate, a different classifier was setup and employed. Classification accuracies were measured via area under the (receiver operating characteristics) curve (AUC). Statistical analyses of the variance between classification accuracies, show that threat stimuli are most accurately separable from non-threat stimuli (Figure 1 (a)) as opposed to distractor (novel) versus non-threat stimuli (Figure 1 (b)), across a range of stimulus categories (i.e., faces, direct threat, and objects and scenes), and for each rate of presentation. Furthermore, the earliest maximal topographical response, observed across broader occipital areas, is elicited in response to direct threat stimuli (Figure 1 (c1), row 1).

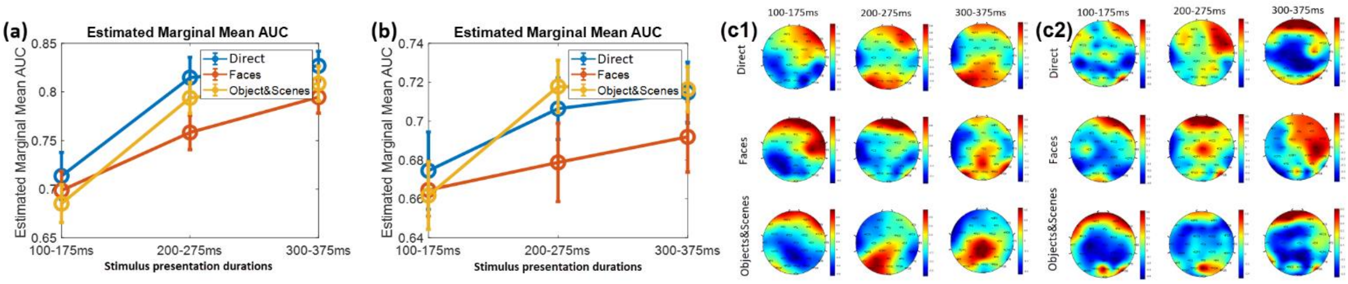

Figure 1. ***RSVP with background and button-press; (a) Threat versus nonthreat and (b) distractor versus nonthreat,*** *presents the estimated marginal means of AUC for classification accuracies – category had 3 levels; direct (blue legend), faces (red legend) and objects&scenes (yellow legend). Presentation rates were 100-175ms, 200-275ms, and 300-375ms.* ***(c1) Threat versus nonthreat and (c2) distractor versus nonthreat,*** *presents a topographical illustration of the cortical activations providing the majority of the information to enhance separability between (c1) threat/ (c2) distractor and non-threat stimuli elicited ERPs, for each category, at each presentation rate.*

Discussion: The findings demonstrate the feasibility of distinguishing threat stimuli from non-threat stimuli, with higher accuracy compared to separating distractor (novel) stimuli from non-threat stimuli, when early event-related potential (ERP) signatures are classified against those for non-threat stimuli.

Significance: These results demonstrate that EEG-based Brain-computer Interface (BCI) technology has the potential to provide a temporal advantage for the detection of threats in dangerous environments.

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BRAND: A platform for real-time deep network inference in closed-loop BCIs

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Introduction: Closed-loop experiments are key components of brain-computer interface (BCI) research. Artificial neural networks (ANN) are state-of-the-art tools for modeling and decoding neural activity, but deploying them in closed-loop experiments is challenging. Researchers need a framework that supports high-level programming languages for running ANN (e.g., Python and Julia) while maintaining support for languages critical for low-latency data acquisition and processing (e.g., C and C++). To address these needs, we introduce the BRAND Realtime Asynchronous Neural Decoding system (BRAND).

Materials, Methods, and Results: BRAND can run on almost any standard Linux computer and comprises processes, termed *nodes*, that communicate with each other via streams of data in a *graph*. BRAND supports reliable real-time execution with microsecond precision, making it an ideal platform for closed-loop neuroscience and neural engineering applications. BRAND uses Redis [1] to send data between nodes, which enables fast inter-process communication (IPC), support for 54 programming languages, and distributed processing across multiple computers. Developers can deploy existing ANN models seamlessly in BRAND with minimal implementation changes. In initial testing, BRAND achieves a fast IPC latency (<500 microseconds) when sending large quantities of data (1024 channels of 30 kHz simulated neural data in 1 ms blocks). BCI control was tested with a graph that receives 30 kHz microelectrode array voltage recordings via Ethernet, filters and thresholds the input to get spikes, bins spikes into 10 ms bins, applies a decoding model, and updates the position of a cursor on a display. In an initial demonstration of the system, participant T11 in the BrainGate2 clinical trial (NCT00912041) achieved a target acquisition time of 2.84 ± 0.83 seconds (53 trials) on a radial-8 center-out cursor control task, in which 30 kHz signal processing, linear decoding, task control, and graphics were all executed in BRAND. Future experiments will incorporate ANN; to benchmark ANN latency, we ran a PyTorch-based recurrent neural network decoder (10 hidden units, 30-bin input sequences) and measured latency (N = 30,000 packets). The end-to-end latency from signal input to decoder prediction was consistently less than 2 ms for this configuration (**Fig. 1**). We also validated that BRAND can run two popular neural population dynamics models – Latent Factor Analysis via Dynamical Systems (LFADS) [2] and Neural Data Transformer (NDT) [3] – in real-time, with latencies below 6 ms per 10 ms bin (256-channel data), using their original Tensorflow and PyTorch implementations.

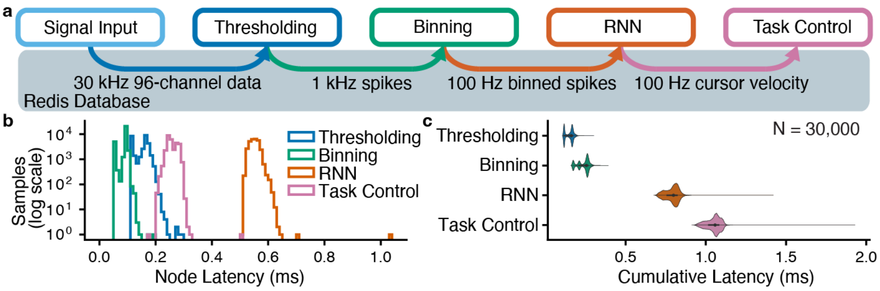

***Figure 1**. a) BRAND nodes in a graph. b) Latency of each node. c) End-to-end latency of the system.*

Discussion: BRAND supports low-latency ANN inference while providing seamless integration with the data acquisition, signal processing, and task code that is needed for closed-loop BCI research.

Significance: With its modular design and broad language support, BRAND simplifies the process of translating computational models from offline analysis into closed-loop experiments that leverage the power of ANNs to improve BCI control across several contexts.

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Feature selection algorithms to optimize corticomuscular coherence-based BCI for hand motor rehabilitation

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Introduction: Recently we explored CorticoMuscular coherence (CMC) as control feature for a hybrid Brain-Computer Interface (BCI) for post-stroke rehabilitation. Results highlighted how the CMC was effective in (i) detecting movement attempts with high classification speed and accuracy [1][2] and (ii) capturing motor abnormalities in stroke patients [3]. Identifying the optimal CMC control features, i.e. couples of electroencephalographic (EEG) and electromyographic (EMG) channels, is mandatory for rehabilitation protocols supported by a hybrid BCI. Here we explored the CMC feature selection process in a sample of healthy participants performing right hand finger extension, comparing two feature selection algorithms: the stepwise regression (SW), already validated in [4] as effective approach in selecting features for a sensorimotor-rhythms based BCI supported motor imagery training, and the decision tree (DT) because of its ease of interpretation.

Material, Methods and Results: EEG (61 channels, 1000Hz) and EMG (8 channels per side, 2000Hz) data were collected from 16 healthy participants while performing 20 trials of right hand movement and 20 trials of rest. EEG and EMG data were pre-processed and CMC was evaluated for each pair and frequency band (α 8-12 Hz, β 13-30 Hz, γ 31-60 Hz) as in [2]. The original feature space for each participant was composed by CMC values extracted for each EEG-EMG couple, trial and band. According to neurophysiological and rehabilitative principles, we reduced such space to the CMC couples considering only the EEG channels over the sensorimotor strip (FC, C, CP, and P electrodes) and EMG from target muscle. The SW and DT algorithms were optimized in their setting parameters and tested in the framework of a 10-iterations cross-validation on the reduced feature space. For each iteration, we shuffled the trials and used 80% of the trials as training set and the remaining 20% as testing set. A linear kernel support vector machine and a decision tree classifier were used as classification models for the SW and DT, respectively. Classification accuracy, sensitivity and specificity were computed for each algorithm and band and statistically compared via 2-way repeated measure ANOVA (within main factors: ALGORITHM - 2 levels and FREQUENCY BAND - 3 levels). Both algorithms returned classification accuracy higher than 90% with no significant differences ($F(1,15)= 0.241$, $p>0.05$). Conversely, statistical differences were found in terms of sensitivity where DT outperformed SW ($F(1,15)=10.8$, $p<0.01$) and specificity where SW outperformed DT ($F(1,15)=13.7$, $p<0.01$). No differences were observed for the FREQUENCY BAND factor. As for the selected features, we computed for each algorithm and frequency band how many times each CMC feature was selected across participants and iterations. Figure 1 shows a spread-out scalp distribution of the features selected by DT. Conversely, the CMC features selected by SW (Fig.1) resulted more consistent across participants and prevalent on the hemi scalp contralateral to the moved hand.

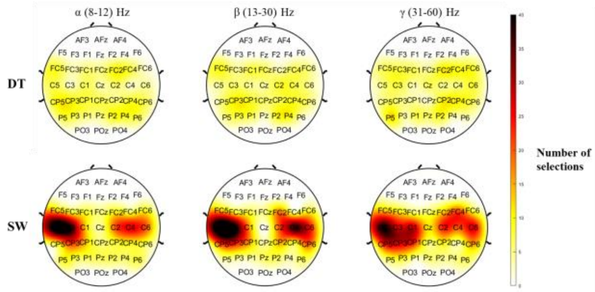

***Figure 1**. Scalp distribution (n=16 healthy participants performing the finger extension of the right hand) of the CMC features selected (EMG counterpart on the target muscle) by means of the Stepwise Regression (SW) and Decision Tree (DT) algorithms for each frequency band (α, β and γ, column). The colour codes for the times each feature was selected across participants and cross-validation iterations*

Discussion: Stepwise regression algorithm returned high (90%) classification accuracy, selecting features consistently across healthy participants. The scalp distribution of the most selected features reflected the neurophysiologic assumption of contralateral sensorimotor cortical involvement during hand motor tasks. Future studies will evaluate the algorithms behaviour with patients' data, to best fulfil neurorehabilitative requirements.

Significance: This work provides hints to optimize the CMC-based BCIs feature selection for post-stroke rehabilitation.

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Network features for motor imagery-based brain-computer interfaces

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Introduction: It is well known that the motor cortex is principally involved in controlling the contralateral side of the body. Most of the motor-based Brain-Computer Interface (BCI) paradigms rely on this spatial layout to decode motor imagery (MI) from brain signals [1]. Furthermore, recent neuroimaging studies demonstrated that also functional connectivity (FC) reveals this lateralization during motor-related tasks [2].

Material, Methods and Results: In this work, we explored the dual contribution of brain network topology and space in modeling MI states through functional lateralization [3]. Specifically, we introduced new network metrics to quantify *integration* (ω) and *segregation* (σ) (Fig. 1-A). These properties respectively account for the contribution of within- and across-hemispheric connections for pairs of homotopic nodes *i* and *j*.

To assess our approach, we used six open-access datasets of healthy participants [4]. This data contains EEG signals measured during MI experiments focusing on left and right hand grasping motions. We estimated spectral coherence-based networks. Then we computed the network lateralization metrics for each electrode. To statistically evaluate the power of these properties in differentiating between MI tasks, we performed a 5000 permutation t-test. We resumed the obtained results in Fig. 1-B.

Discussion: This analysis enabled us to identify the most discriminant electrodes. Both metrics engage a subset of nodes mostly located in the M1 cortex, but also the PMA, SMA and S1 areas which are crucial in the planification and execution of a movement. We observe that ω shows higher values over the motor cortex, while σ also involves frontal areas, usually associated with attention and motor planning.

Significance: In the BCI classification scenario, these network properties not only can improve the overall accuracy, but they also have the advantage of being neurophysiologically interpretable, compared to state-of-the-art approaches, like CSP and Riemannian methods, that are instead blind to the underlying mechanisms. These results show the neurophysiological plausibility of our proposed network approach. Moreover, they prove to be highly relevant features for decoding a MI mental task.

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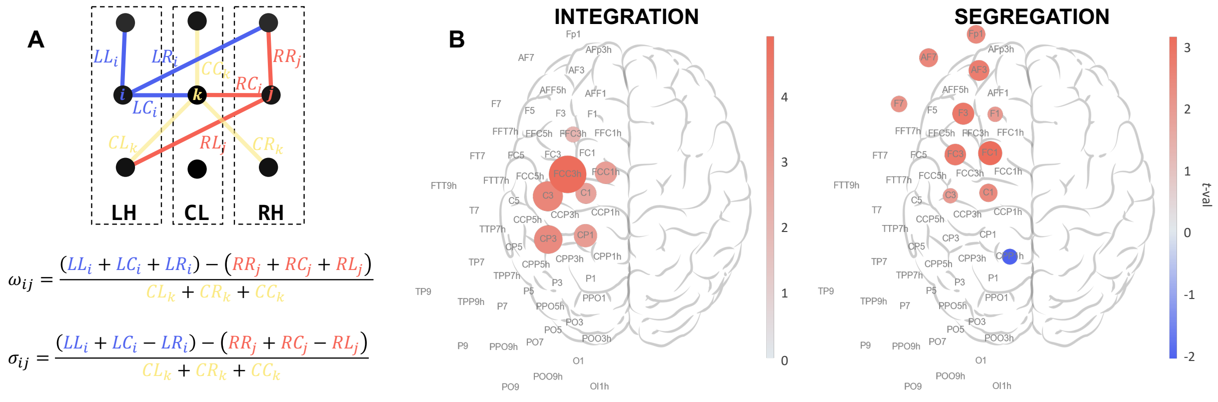

$$\omega_{ij} = \frac{(LL_i + LC_i + LR_i) - (RR_j + RC_j + RL_j)}{CL_k + CR_k + CC_k}$$

$$\sigma_{ij} = \frac{(LL_i + LC_i - LR_i) - (RR_j + RC_j - RL_j)}{CL_k + CR_k + CC_k}$$

Figure 1. A- *. Integration (ω) and segregation (σ). Each term represents the strength of a node in the homotopic pair i and j. More precisely, the capital letters respectively denote the locations of node i and the nodes it establishes connections with (e.g., LR_i means that node i belongs to the left hemisphere and we consider the connections that link it to the right hemisphere nodes). Note that for the particular case of brain signals recorded with an EEG system, the electrodes placed in the midline sagittal plane (C_k) do not strictly belong to a hemisphere, then we consider them to normalize the metrics values. LH: left hemisphere, RH: right hemisphere and CL: central line.* ***B-*** *Group-averaged node-t-values between right and left MI mental states. By definition, lateralization metrics are anti-symmetric with respect to the hemispheres. For the sake of simplicity, only the left hemisphere is shown in here.*

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Predicting high-quality movements in post-stroke motor rehabilitation from EEG

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Introduction: A promising new concept for post-stroke motor rehabilitation is using EEG-based brain-computer interface (BCI) systems [1], e.g., providing patients with EEG-based feedback on their decoded movement intent [2]. Here, we explore the possibility of extending BCI-based rehabilitation paradigms from decoding movement intent to decoding movement quality. Toward this goal, we study whether the quality of hand opening and closing movements in stroke patients with arm and hand spasticity can be decoded from their EEG.

Material, Methods, and Results: We investigated twelve patients with chronic stroke and hand spasticity performing hand opening/closing tasks. To quantitatively assess the quality of the hand movements, the muscular activity during the patients' hand movement was measured with three EMG electrodes. We investigated the EEG by computing the band power of individual mu-rhythms and divided the tasks into high- and low-quality classes according to their EMG power. We applied a standard LDA classifier with a 10-times 10-fold CV and CSP to predict the movement quality with mu-power as a feature. Our classification model reached a group-level accuracy of around 90% predicting high- versus low-quality movements throughout different trial phases.

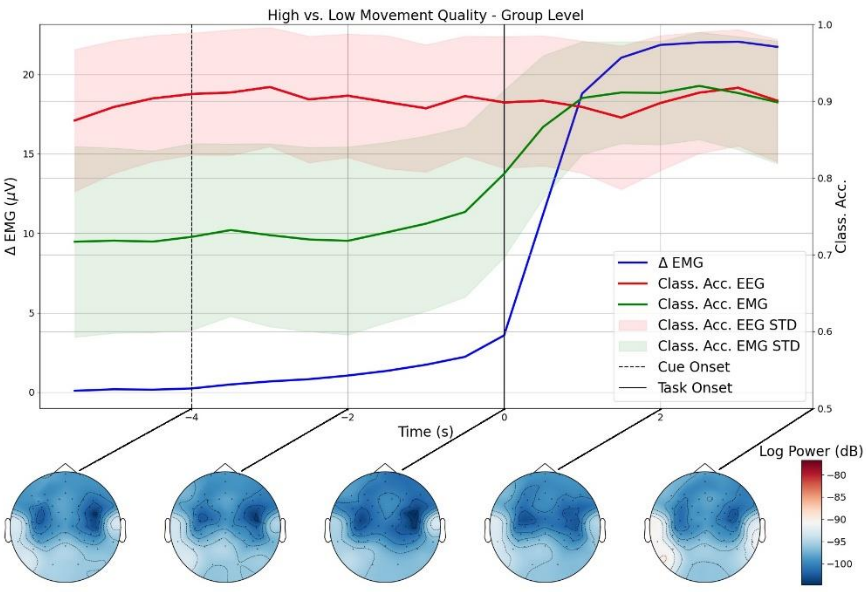

***Figure 1**. High- vs. low-quality movement prediction, EMG power, and mu-power topographies*

Discussion: Using µ-power as a feature for our classification model, we could reach a classification accuracy of around 90% throughout different trial phases, whereas the accuracy of classifying EMG power increases at task onset and only reaches 90% during task execution. Also, the sequence of mu-power topographies indicates that differences in brain activity patterns occur even before the start of the movement. These findings can be used to apply our model to an online BCI system, where the patients receive feedback on their brain activity before the actual onset of the movement task, which can focus their attention on the task execution and improve the rehabilitation progress.

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Using transient, modality-specific neural responses to enhance decoding

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Introduction: The real-world implementation of brain-computer interfaces (BCI) for use in e.g. computer access should ideally rely on fully asynchronous decoding approaches. That is, the decoding algorithm should continuously update its output by estimating the user's intended actions from real-time neural activity, without any temporal alignment to an external cue. This kind of open-ended temporal flexibility is necessary to achieve naturalistic control, but presents a challenge: how do we know when it is appropriate to decode anything at all? Activity in motor cortex is dynamic and contains a heterogeneous mix of different control modalities (proximal arm, hand, speech, etc.) that can interfere with each other. Because of this, the "decodability" of any given action type (amount of relevant information present in the activity) fluctuates over time based on motor intent as well as intrinsic network dynamics. Here we present a method for simplifying the problem of decoder generalization that uses transient, modality-specific neural responses to first identify periods of modality engagement (e.g. "hand-related"). Only then do we decode specific features of that modality (e.g. digit or force). By using this two-stage approach, decoding models can be simpler (owing to local linearity) and are less sensitive to cross-modality interference.

Material, Methods and Results: We recorded intracortical activity from chronic microelectrode arrays (Blackrock Microsystems) in the primary motor cortex (M1) of two human participants with tetraplegia as they attempted arm- and hand-related tasks. The tasks included a mixture of covert proximal arm translation, individual finger presses, and full-hand grasp at different force levels. We found widespread transient responses at the onset and offset of all hand-related gestures that were nonspecific to the digit or force level (Figure 1a, top). We also found that the amount of available information regarding the specific digit(s) used and/or grasp force level peaked at the onset of a gesture and then steadily decreased until offset (Figure 1b). Based on these findings, we created a multi-level decoding approach for hand gestures that engages decoders for digit and/or force only after identifying a hand-related onset transient (Figure 1a, bottom). By restricting the decoder to operate only on relevant temporal epochs (indicated in Figure 1b), simple linear methods for both digit and force decoding were able to provide high quality control (0.1 errors per decoded gesture for both digit and force, compared to 3.6 and 16.2 errors per decoded gesture when using standard classification).

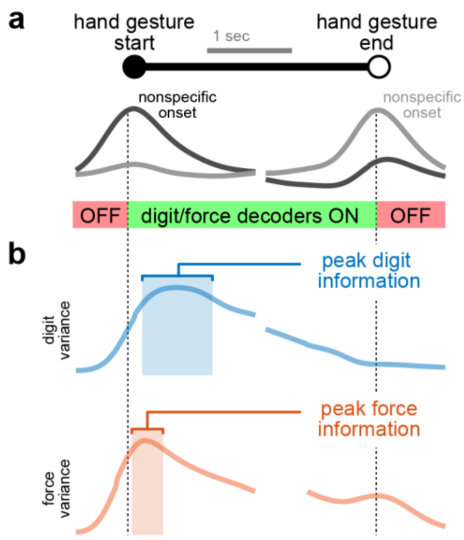

Figure 1. Modality-specific transients indicate upcoming periods of high information content. ***a*** *The participant performed tasks involving finger and grasp force gestures. Transient hand-specific responses—nonspecific to either digit or force level—existed at the onset and offset of gestures, which were used to enable and disable detailed decoding* ***b*** *The population activity contained decreasing information about finger and force throughout the gestures*

Discussion: Under controlled conditions, motor cortical activity often contains linear relationships with kinetic and kinematic variables. However, these simple relationships often break down during complex, free-behavior (like during real-world control). Here we show a nested, multi-layer method for dealing with nonlinearities during multi-modal BCI decoding.

Significance: Reliable control spanning multiple modalities (e.g. arm and hand) is essential for successful BCI application. We found that nonspecific transient responses related to modality engagement can be used to supplement decoding approaches and improve performance.

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Broca's Area: A Single-Unit Recording Perspective

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Introduction: Left inferior frontal gyrus (LIFG), encompassing Broca's area, has long been associated with human speech and language, including articulation. Furthermore, LIFG has more broadly been implicated in diverse functions of human cognition extending beyond speech, language and grammatical processing to tasks like rhythm processing, arithmetic, working memory, and more [1,2]. While functional MRI (fMRI) has paved the way in attributing such diverse cognitive functionality to this region of the brain, understanding the exact role LIFG plays in these diverse tasks of human cognition requires greater spatial and temporal resolution. Here we present early data from the first LIFG recordings from intracortical microelectrode arrays during cognitive tasks historically associated with the region.

Material, Methods and Results: A Braingate participant ("T12") with anarthria due to bulbar ALS received two Utah arrays in LIFG and two in ventral precentral gyrus. T12 is left-handed but exhibited strong left-sided language processing on fMRI. Most tasks included in this study were conducted in an instructed-delay paradigm: each trial was cued with either displayed text or an audio recording during a 'delay' period followed by a 'go' period, during which the participant attempted to vocalize the answer to the prompt or perform the desired action. We have to date collected microelectrode array recordings during tasks involving simple instructed movements (e.g., "close your hand"); speaking, reading, and listening to words and sentences; free-response speech; rhythm and melody; arithmetic; grammatical processing; spelling; action imitation and observation; sequential and bimanual gestures; as well as the classic Stroop task. Notably, we found that while LIFG recordings showed increased modulation during listening and speaking tasks as compared to resting state, there was little to no cross-condition modulation differences that would demonstrate that LIFG plays a strong role in producing or interpreting the content of what was being spoken or heard. LIFG was also not strongly modulated for simple instructed movements. This was in contrast to other tasks that showed high cross-condition modulation, including a spelling task in which T12 was instructed to spell a word aloud either forwards or backwards, a grammar fill-in task in which T12 was instructed to complete a sentence with a root word while applying any necessary semantic or phonological changes to the root word, and an action imitation task in which T12 had to imitate short sequences of gestures or sign language (not previously known to the participant).

Discussion: The results from T12's LIFG microelectrode array recordings implicate LIFG as having a role in a variety of cognitive tasks, including tasks that do not involve language or speaking. Federenko et al 2020 summarize a large body of previous fMRI literature and propose that Broca's area contains two functionally-distinct subregions, a "language network" and a domain-general "multiple-demand network." Our preliminary findings in T12, which show little cross-condition modulation for low-level speech articulation, but large cross-condition modulation for higher-level cognitive tasks align well with this proposal, with the possibility that T12's arrays are in the domain-general region of LIFG. Further data collection and analysis will aim to elucidate any unifying role that LIFG may play in the diverse set of cognitive tasks for which it has been implicated, including language, speech planning and production.

Significance: High-resolution neural ensemble recordings in LIFG in a person with anarthria due to ALS afford a new, in-depth perspective on the role of LIFG in general human cognition.

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Biomimetic Intracortical Microstimulation Improves Percept Naturalness in Humans

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Introduction: Without tactile sensation, even simple, everyday tasks are nearly impossible [1]. Intracortical microstimulation (ICMS) in the human somatosensory cortex (S1) provides an innovative way to restore tactile sensations by using electrical stimulation to activate sensory neurons in the brain that would normally respond to touch [2]. ICMS evokes vivid tactile percepts from paralyzed limbs and significantly improves control of BCI controlled limbs [3]. However, it remains unclear how 'natural' ICMS-evoked percepts are and whether different stimulation paradigms can modify naturalness. In this work, we use both mechanical stimulation and ICMS in a psychophysical task to determine the effects of biomimetic ICMS on naturalness.

Material, Methods and Results: Two microelectrode arrays were implanted in both the motor and somatosensory cortices of 2 participants with tetraplegia. Both participants retained some cutaneous sensations from their hands. In a two-alternative forced choice task, participants were presented with a mechanical indentation to sensate skin on their hand followed by two ICMS trains. The mechanical stimulus was 1 s long and indented the skin to a depth of 2 mm at a rate of 10 mm/s. The ICMS trains were presented in a random order and used either a linear or biomimetic encoding scheme at 250 Hz. The biomimetic trains captured essential features of neural activity in S1 during touch and consisted of a transient phase at the beginning and end of the train, each lasting 0.2 s at an amplitude of 80 µA. Between the transients, the amplitude was 40 µA. In the linear trains, the stimulus amplitude profile matched the mechanical indentation and the maximum stimulation amplitude was set either to the amplitude during the hold phase of the biomimetic train (40 µA), or to match the total charge during the biomimetic train (70 µA). After the two ICMS trains, the participant was asked which train felt more like the reference mechanical stimulus. Preliminary results show that biomimetic stimulation encoding feels more natural compared to both control linear trains ($n = 8$ electrodes, $p < 0.05$, chi-squared test).

Discussion: These experiments demonstrate that study participants are able to directly compare tactile percepts evoked by ICMS and mechanical input, and more importantly, that biomimetic stimuli feel more like actual physical touch than linearly encoded stimulation trains. We interpret these results to mean that biomimetic stimuli are perceived as being more natural. Future experiments will expand these experiments to additional electrodes and participants.

Significance: A better understanding of how stimulation parameters and encoding schemes modulate naturalness will help ICMS more closely mimic natural sensations and improve the quality of restored sensation.

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Enriched sensorimotor feedback modalities may increase upper extremity motor recovery in stroke survivors using brain-computer interface-mediated functional electrical stimulation

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Introduction: Brain-computer interface (BCI)-mediated functional electrical stimulation (FES) of the stroke impaired upper extremity is thought to improve motor capacity through neuroplasticity. Of the various device designs, BCI interventions utilizing paired FES of the stroke impaired extremity typically result in superior increases in mobility compared to other BCI designs. However, it is not known whether BCI-FES devices are superior because they superficially link task-directed intent to move brain changes with peripheral muscle activation or, because the multimodal feedback inherent to BCI-FES designs allows a richer learning environment with more afferent sensory input to sensorimotor brain areas, which may result in better learning. The present preliminary analysis sought to determine if additional sensory feedback of BCI task performance, via electro-tactile stimulation in the form of a tongue display unit (TDU), results in greater motor recovery.

Material, Methods and Results: In order to test whether increased sensory feedback leads to greater motor recovery, we compared *post hoc* groupings from our larger study cohort where some individuals received BCI-FES and others received BCI-FES-TDU. Data were acquired from 25 stroke survivors (n = 25, 12 females, age = 64.0 ± 12.1 yr, mean ± SD), who are part of a larger on-going study. A BCI-FES-TDU group (n = 18) and a BCI-FES group (n = 7) received up to 30 hours of BCI intervention. All participants were assessed at baseline and completion with behavioral measures which included the Action Research Arm Test (ARAT). Changes in group mean ARAT total score of the impaired upper extremity were calculated and compared using an independent samples t-test. The mean change in ARAT total score increased for participants who received BCI-FES-TDU intervention (difference = +2.28 ± 4.21, mean ± SD). In contrast, no such increase in total ARAT total score was observed for the BCI-FES group (difference = +0.71 ± 3.30, mean ± SD). The difference in mean change between the two groups, however, was not statistically significant (t = 0.98, df =14, p = 0.344).

Discussion and Significance: For stroke survivors with upper extremity motor impairment, both BCI-FES-TDU intervention and BCI-FES intervention may be effective methods for motor recovery, and increased sensory feedback provided in the BCI-FES-TDU intervention may lead to additional recovery. However, more research into the neural mechanisms behind these measured differences is required.

Acknowledgements: The authors would like to thank and acknowledge the study participants and their families and caretakers for their time and participation.

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Effectiveness of cross-frequency phase-amplitude covariance as additional features for Riemannian BCIs

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Introduction: Riemannian geometry has been shown to significantly improve BCI classification performance [1]. However, BCIs are still not reliable enough. To further improve Riemannian BCIs, it is thus worth exploring complementary features to the conventional Riemannian feature, i.e., spatial covariance matrix. In this work, we propose to combine the phase and amplitude covariance (PAC) of cross-frequency bands (FBs) as such an additional feature, inspired by phase-amplitude coupling [2].

Material, Methods and Results: We propose a new symmetric positive definite (SPD) matrix P_{PAC+BP}, that considers multiple features based on phase, amplitude, and band power (BP) of cross-FBs in one covariance matrix (Cov). As summarized in Fig. 1, P_{PAC+BP} consists of two different block matrices P_{PAC} and P_{BP} diagonally arranged with null off-diagonal matrices. P_{PAC} quantifies the covariance between the phase of low FB (LF) and the amplitude of high FB (HF). The best FB pair LF-HF is selected among 6 pairs (δ-β, θ-β, α-β, δ-γ, θ-γ, α-γ, β-γ) using the classDis FB selection algorithm from [3]. P_{BP} arranges the conventional spatial Covs in LF and HF diagonally as block matrices. We evaluated the usefulness of P_{PAC+BP} for mental workload classification using a public passive BCI dataset from [4]. To investigate the contributions of PAC and BP features, we also compared performances of P_{PAC} and P_{BP} individually. As a baseline, we built a Cov with the same structure as P_{BP} but with θ and α bands, the two most used FBs for EEG-based mental workload classification. Artifacts from that EEG dataset were reduced using ICA.

P_{PAC}: **cross-frequency phase and amplitude Cov.**

$$X_{PAC} = \begin{pmatrix} \cos(\phi_{f_L}(t)) \\ \sin(\phi_{f_L}(t)) \\ a_{f_H}(t) \end{pmatrix} \in \mathbb{R}^{3N\times T}$$

$$P_{PAC} = \frac{1}{T-1} X_{PAC} X_{PAC}^{\top} \in \mathbb{R}^{3N\times 3N}$$

$\phi_{f_L}(t)$ …phase of low frequency band

$a_{f_H}(t)$…amplitude of high frequency band

P_{BP}: **cross-frequency band-power Cov.**

$$\Sigma_{X_{f_L}} = \frac{1}{T-1} X_{f_L} X_{f_L}^{\top} \in \mathbb{R}^{N\times N}$$

$$\Sigma_{X_{f_H}} = \frac{1}{T-1} X_{f_H} X_{f_H}^{\top} \in \mathbb{R}^{N\times N}$$

$$P_{BP} = \begin{pmatrix} \Sigma_{X_{f_L}} & 0 \\ 0 & \Sigma_{X_{f_H}} \end{pmatrix} \in \mathbb{R}^{2N\times 2N}$$

$X_{f_L}(t)$…filtered EEG at low frequency band

$X_{f_H}(t)$…filtered EEG at high frequency band

P_{PAC+BP}: **combined Cov. of P_{PAC} and P_{BP}**

$$P_{PAC+BP} = \begin{pmatrix} P_{PAC} & 0 \\ 0 & P_{BP} \end{pmatrix} \in \mathbb{R}^{5N\times 5N}$$

Figure 1. *Formulas of proposed cross-frequency SPD matrices*

The dataset consisted of EEG data from 29 subjects who performed zero or two back tasks. The first two blocks were used as the training set, and the final block as the test set. Mean classification accuracies (%) using Minimum Distance to Mean classifier [1] were 74.1±15.1, 76.6±20.6, 78.5±21.4 and 84.4±18.4 for the baseline, P_{PAC}, P_{BP}, and P_{PAC+BP} respectively. Repeated measure ANOVA revealed significant differences between methods (p = 0.01). P_{PAC+BP} showed statistically significant improvement from baseline (p=0.01). ***Discussion:*** All Cov showed better mean accuracy than baseline, with P_{PAC+BP} showing the greatest improvement. This suggests the effectiveness of PAC as an additional feature to BP.

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Let's Move: Case Studies in Learning Basic Power Mobility Skills Using BCI

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***Introduction*:** Exploration of powered mobility devices (PMDs) can enhance inclusion, autonomy, and overall quality of life for children with severe physical disabilities [1]. However, traditional PMD access methods, such as joysticks or switches, require some degree of motor control to operate [2]. Brain-computer interface (BCI) systems offer a potential PMD access solution for children with severely limited motor control [3]. BCi-Move is an ongoing, multi-center, longitudinal case study exploring how commercial-grade BCI systems can be integrated into a personalized therapeutic framework to help such children achieve personal mobility goals.

Figure 1: Participant playing a Harry Potter Quidditch game with his caregiver during a BCI-Move training session, working on driving forward and stopping.

Materials, Methods, and Results: 30 children with severe physical disabilities will be recruited across 4 sites to participate in the BCi-Move study. Participants first identify personalized power mobility goals and then participate in a 12-week training program to develop both power mobility and BCI skills. Two children have completed the entire training program. The 14-channel, saline-based, wireless Emotiv Flex and the Emotiv Epoc X headsets were used for the BCI hardware, and a motor imagery BCI paradigm was used with 12 calibration runs at the start of each session. The Flex cap was modified to maximize the fit and contact quality for participants as required. Participants then engaged in motivating and skill-building activities, working towards their personalized power mobility goals (Fig. 1). Goal Attainment Scaling (GAS) was used to measure progress towards goal achievement, and the Assessment of Learning Powered (ALP) mobility instrument was used to score power mobility skill development. Participants reported workload experiences using a modified NASA-TLX and family/caregivers ranked participant and clinician engagement. ALP scores indicated some improvement in power mobility skills. Participants highly rated their satisfaction and perceived performance on their personalized mobility goals, but reported some frustration due to technical issues and troubleshooting during the sessions. Participants consistently rated high levels of engagement over the training sessions.

***Discussion*:** Early results suggest that personalized goals and training for power mobility can facilitate the development of PMD skills for children with physical disabilities using BCIs. Engagement and perceived performance measures indicate that power mobility can be an engaging and motivating task for BCI skill development. However, participant frustrations highlight that BCI-enabled power mobility can be further optimized for use by children with severe physical disabilities.

***Significance**:* Participant-centered, longitudinal multi-site trials exploring movement and learning BCI power mobility and potential impactful for children with severe disabilities.

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GRASP FORCE IS ENCODED IN DYNAMICAL PATTERNS OF ACTIVITY IN THE MOTOR CORTEX OF MONKEYS AND HUMANS

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Introduction: From prehension to pianism, object interactions require precise control of both the movements of the hand and of the forces it exerts on objects. Recent work shows that time-varying posture of the hand is encoded in the activity of populations of neurons in primary motor cortex (M1) and these signals can be harnessed to decode hand kinematics for intracortical Brain Computer Interfaces (iBCI) to restore limb function to patients with spinal cord injury. However, much less is known about how manual forces are encoded in M1, which severely limits the capability of iBCIs to support object interactions that require precise and graded force application. The aim of this study is to first understand how manual forces are encoded in M1 of able-bodied behaving macaques and then apply the insights gleaned from our experiments to build biomimetic decoders of manual force in patients with tetraplegia.

Material, Methods and Results: To investigate how manual forces are encoded in M1 during object interactions, we first recorded the neural activity in M1 as monkeys grasped sensorized objects and characterized the force signal in this population. We found that dependence between force and motor signals is governed by non-linear dynamics that can be exploited for force decoder design. Next, we applied the insights gleaned from our experiments with able-bodied macaques to build decoders of manual force in three human participants with tetraplegia. In brief, we instructed the participants to grasp virtual objects with varying amounts of force while we monitored their M1 activity via chronically implanted electrode arrays. We found that the patterns of responses in human M1 during imagined force application were similar to those in monkey M1 during physical force application. We then built real time decoders that harness force signals in M1 to allow the participants to exert forces with the virtual hand. We show that decoders of force that can exploit non-linear dynamics in the M1 response significantly outperform standard linear or non-linear methods both offline and in real time applications.

Discussion and Significance: These results pave the way for brain-controlled bionic hands that allow the user not only to precisely shape the hand but also to apply well-controlled forces with it.

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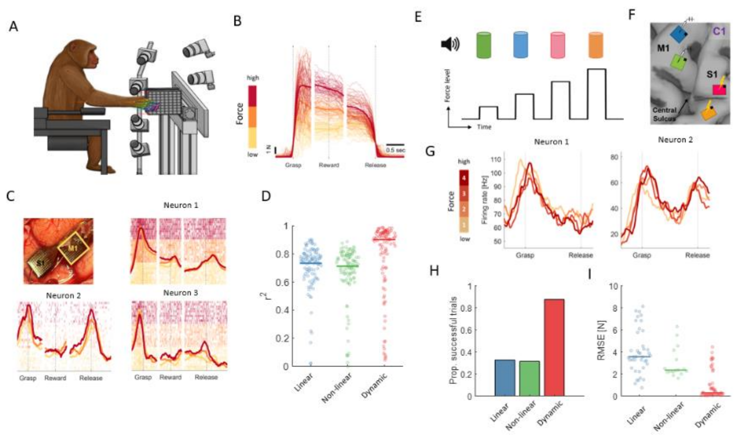

Figure 1. A-D Monkey experiments. E-I Human experiments. A| Experiment setup. Two monkeys were trained to reach for and grasp an object with instructed amount of force. B| Single trial force profiles color-coded by instructed force level. C| Three example raster plots and PSTHs of motor cortical neurons color-coded by target force. Inset: Utah electrode array placement in one of the monkeys. D| Distribution of cross-validated correlations for all trials decoded with Linear, Non-linear and Dynamics decoders in monkey data. E| Human BCI experiment. The subject is instructed to attempt to grasp the virtual object with one of four linearly spaced force levels cued by the color and a verbal command. F| Array placement in one of the subjects. G| Example PSTHs aligned to onset of virtual movement of the avatar limb during observation stage. Lines are color-coded by target force level. H| Proportion of correct trials with Linear, Non-linear and Dynamics decoders. I| Error of online force production with Linear, Non-linear and Dynamics decoders.

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Development of an iBCI System for Control of a Soft Robotic Glove

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Introduction: Intracortical brain-computer interfaces (iBCIs) use signals recorded directly from the brain to help individuals with paralysis to control assistive devices such as computer cursors or robotic arms. For people with tetraplegia, an opportunity for iBCI systems is to provide for the intuitive reanimation of one's own limb and incorporating, for some users, residual proprioceptive feedback. In addition to ongoing work with functional electrical stimulation systems, the recent emergence of soft robotic technology has enabled the development of soft, wearable exoskeletons that, when paired with a reliable control signal, could be used to restore movement in people with severe motor impairment. In this study, we demonstrated the successful use of an iBCI system to provide basic movement of the hand via a soft robotic glove (SRG). We have also begun to investigate the effects of somatosensation and its effects on motor cortex-enabled, SRG-assisted hand control.

Materials, Methods, and Results: Experimental sessions were performed by participant T11, a 38-year-old, right-handed man with a spinal cord injury (C4 AIS-B). T11 had two 96-electrode arrays implanted in his left precentral gyrus as part of the BrainGate Clinical Trial. A fabric-based, pneumatically actuated glove and controller system were manufactured and programmed to provide 4 functionally relevant grip states: power grip, pinch grip, open hand, and relax. As part of our investigation, we recorded neural responses in the motor cortex when T11 attempted or passively observed the SRG perform grips on his own hand vs. a mannequin hand. Although significant neural modulation occurred during visual or somatosensory feedback alone, sensory feedback did not produce significant effects on offline or online decoding of attempted hand grips (LDA-HMM). We also investigated the performance of two robotic control strategies: a "Continuous" controller where SRG postures reflect continuously decoded estimates of intended grip type, and a "Toggle" controller where transient gesture attempts are used to *toggle* between SRG end postures. Both controllers performed well in assessments of grip-switching speed and object transfers, but the Toggle controller allowed T11 to hold grip postures for longer periods of time and was preferred by the participant.

Discussion: The lack of interference of SRG-induced sensory input in decoding of intended grip in this individual is an encouraging sign that existing iBCI strategies for operating external robots could translate well to control of soft robotic exoskeletons. T11's preference for the more robot-like "Toggle" controller raises interesting questions about how to balance the promise of restoring intuitive control of one's own hand with the functional performance of such a system. These questions will be important to ask across individuals with different degrees of sensorimotor impairment and different etiologies of paralysis.

Significance: Soft robotic exoskeletons hold extraordinary promise as avenues for restoration of movement in people with tetraplegia. Here we demonstrate the viability of using iBCI control to operate a soft robotic glove, laying the foundation for future research combining iBCIs with this exciting new class of effectors.

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Automatic Tagging of BCI Artefacts using Computer Vision

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Introduction: Brain-computer interfaces (BCIs) are a rapidly growing field of research that aims to develop new ways for people to interact with technology using brain signals. However, one of the major challenges in BCI research is dealing with artefacts in the signals, such as those caused by head movement, eye gaze, and eye blinks. These artefacts can significantly affect the accuracy and reliability of BCI systems, making it essential to detect and remove them from the signals. Our approach for dealing with these artefacts is to capture video of the participant using a webcam and to use computer vision techniques to automatically detect and measure head movement, eye gaze, and eye opening changes. This can be then used for the automatic tagging of artefacts in the signal data.

Material Methods and Results: The method proposed in this abstract is to capture video of the participant with a webcam and using the video to measure head movement, eye gaze and eye opening changes. The video is then processed using OpenCV algorithms to extract relevant features, such as the position of the head, the direction of the gaze, and the size of the pupils. These features are then compared to baselines and used to automatically detect and tag artefacts in the BCI signals. The results of this method were evaluated using a dataset of BCI signals collected from 10 participants. The signals were manually tagged for artefacts by two independent raters and were also automatically tagged using the proposed method. The results showed that the proposed method was able to accurately detect and tag artefacts in the BCI signals, with an overall accuracy of 95%. This is statistically better than the manually tagged signals, which had an overall accuracy of 82%.

Discussion: In addition to the improved accuracy, the proposed method also has several other advantages over manual tagging. For example, it is faster and more efficient than manual tagging, as it can be done automatically and in real-time. It also reduces the subjectivity and variability of manual tagging, as the results are based on objective measurements of head movement, eye gaze and eye opening changes.

Significance: The proposed method for automatically tagging artefacts in BCI signals by computer vision is more accurate, faster and more efficient than manual tagging. This has the potential to be integrated into, for example, Independent Component Analysis (ICA) systems to automatically remove artefacts in a closed loop system and improve accuracy and reliability of BCI data.

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Leveraging deep state-space models for silent speech decoding

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Introduction: Silent speech interfaces (SSIs) are a promising approach for people with communication disorders. Noninvasive studies have focused heavily on surface electromyography (sEMG) for obtaining electrical signals from orofacial muscles but often rely on handcrafted input features and smaller machine learning pipelines [1, 2]. In this work, we use grids of flexible, hydrogel-based sEMG electrodes to obtain high signal-to-noise ratio (SNR) recordings during silent speech production, and a recent class of machine learning models developed for long time-series inference [3] to decode these recordings.

Methods: We applied grids of hydrogel-based sEMG sensors to a volunteer's face as they silently uttered a dataset of fifty words in an instructed delay task. Simultaneous activity from 48 sEMG channels across the arrays were recorded at 30 KHz. Signals were digitally filtered offline using a 5th order Butterworth 1 Hz highpass filter and downsampled to 1 KHz.

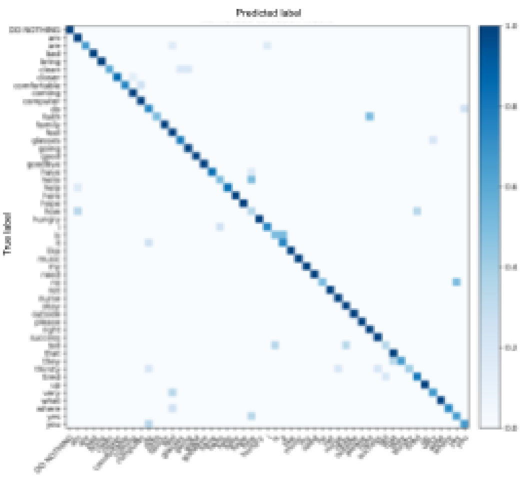

Fig. 1: normalized S4 confusion matrix (84% acc)

Results: Using a ConvMLP model, we obtained a 33% absolute improvement in fifty-way classification over a logistic regression with manually-derived features in. Furthermore, a deep learning model specifically designed to incorporate long timescales (‘S4’) improved accuracy by an additional 8%, with an overall accuracy of 84%. We demonstrated increasing accuracy with increasing channel count and dataset size.

Discussion: S4’s performance highlights the potential for deep state-space models in SSIs and, more broadly, extracting nonlinear features from raw EMG activity. Hyperparameter sweeps indicate that higher performance is likely achievable with increased channel counts and training data.

Significance: Our results indicate that deep state-space models are well-suited for sEMG-based silent speech decoding. Increasing performance with higher channel count and more data suggests room for future improvements by leveraging higher-density arrays and continuous speech corpuses.

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At-home, embedded closed-loop deep brain stimulation using data-driven neural physiomarkers alleviates residual motor symptoms in Parkinson's disease

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Introduction: Deep brain stimulation (DBS) is a surgical therapy for patients with Parkinson's disease. However, standard-of-care continuous DBS may be associated with residual motor fluctuations, especially as patients transition throughout their levodopa medication cycle. Closed-loop DBS can automatically respond to motor fluctuations by adjusting stimulation amplitude in response to a neural physiomarker – a neural signature which reflects either medication state or motor symptoms. Prior closed-loop studies have been limited to perioperative environments that may not reflect naturalistic settings [1], and predefined frequency bands that may not be optimal physiomarkers for patient-specific symptoms [1], [2]. We sought to derive individualized neural physiomarkers based on at-home neural recordings and symptom monitoring, while implementing embedded closed-loop DBS in the home environment.

Materials, Methods and Results: Participants (n=5) were implanted with permanent subthalamic and sensorimotor cortical leads connected to a second-generation bidirectional device (Medtronic Summit™ RC+S). The RC+S has the capability of sensing neural signals while simultaneously delivering therapeutic stimulation [2]. We recorded local field potentials from the subthalamic nucleus and sensorimotor cortex via a patient-facing graphical user interface [2] and paired recordings with wearable monitors that assessed motor symptoms [3], [4] while participants performed activities of daily living. The most discriminative physiomarker of medication state or symptom was derived for each participant using a linear discriminant classifier with sequential forward feature selection [5] and cluster-based analyses controlling for stimulation effects on the neural signal [6]. During at-home implementation, we randomized testing days between continuous and closed-loop DBS while participants were blinded to the condition. At the end of each testing day, participants rated the number of awake hours and severity of their most bothersome motor symptom. These varied between individuals and included dyskinesia, bradykinesia, tremor, and dystonia. Data-driven physiomarker identification also varied between individuals and included cortical gamma (64-66 Hz and 64-70 Hz), subthalamic alpha/beta (11-15 Hz), subthalamic gamma (64-66 Hz), and cortical theta/alpha (2-10 Hz). Across participants and testing days, the average percentage of awake time spent with the most bothersome symptom decreased during closed-loop DBS compared to continuous stimulation (14.37% vs 35.82%, $p < 0.01$), as did the average severity of the symptom (1.72 vs 2.70, $p < 0.05$; scale 0-10).

Discussion: These results provide single-blinded evidence that embedded, neural-driven closed-loop DBS can reduce residual motor symptoms - both time and severity - compared to standard-of-care continuous stimulation.

Significance: Closed-loop DBS is translatable to the home environment and is facilitated by multi-site signal detection (cortex as well as basal ganglia). Future steps of this protocol involve the first long-term, at-home double-blind comparison between closed-loop and continuous stimulation.

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Decoding attempted movements from human motor cortical activity recorded with a Stentrode

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Introduction: The Stentrode is a novel endovascular brain-computer interface (BCI) that is implanted endovascularly to record bilaterally from the primary motor cortex. The first-in-human trial (n=4) of the Stentrode demonstrated computer control and digital communication in people with amyotrophic lateral sclerosis (ALS) [1, 2]. An Early Feasibility clinical trial (NCT 05035823) began in the United States (US) in July 2022. Here, we demonstrate offline decoding of attempted movement patterns from the Stentrode electroencephalogram (EEG) recorded from the first participant in the US trial.

Material + Methods: In the US trial, three participants with ALS have been implanted with the Stentrode-BCI via a minimally invasive procedure, where a stent embedded with 16 electrodes was deployed into the superior sagittal sinus adjacent to the motor cortex. Data acquisition and system training with the Stentrode began approximately 7 weeks after implantation. The participants underwent training tasks that consisted of 5-s (± 1 s) rest periods followed by a 5-s period of movement attempt, in which 5 repetitions of attempted movement occurred. The movements attempted were: right ankle, left ankle, right hand, and left hand. The data were bandpass filtered (1-500 Hz), notch filtered at 60 Hz, and segmented into 200 ms windows with 80% overlap. A Neural Network (NN) was implemented to classify the data offline into balanced classes of either rest or one of the attempted movements.

Results + Discussion: Here we present early results from the first US participant. This work shows the ability to record motor-related activity with the Stentrode. *Fig 1 A* shows an example of the EEG signals spatially filtered with PCA. Unlike previously reported results [1,2], data from this participant shows synchronization of beta and low gamma during attempted moments. *Fig 1 B* shows classification accuracy from one day of neuroprosthesis training, with 18 repetitions of each movement. The 2-, 3-, and 5-class models all performed above the level of chance. However, only the 2-class model performed at a level suitable for BCI use (ie >80% accuracy). Furthermore, the bandpass filtered signals were utilized directly as features fed into the NN, demonstrating an end-to-end model without the need for explicit feature extraction.

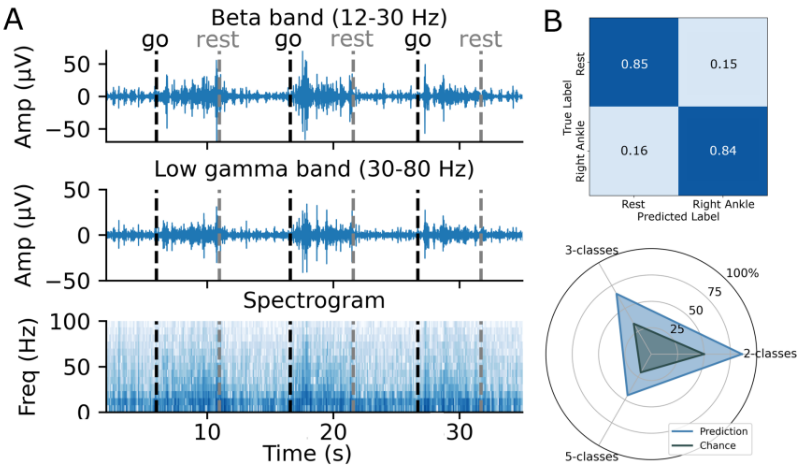

Figure 1. A. *Example data of the first principal component from one participant, while attempting movement of their right ankle.* ***B.*** *Offline classification accuracy and example confusion matrix from one day of motor prosthesis training.*

Significance: Clinical trials of the Stentrode BCI are now underway at 3 sites. Results demonstrate successful decoding of motor intent from endovascular EEG signals recorded from participants with severe paralysis due to ALS. This work demonstrates offline decoding of motor attempts using a NN as an end-to-end model that extracts features and performs classification in a single step.

Acknowledgements: This work was supported by the National Institutes of Health (NIH) (UH3NS120191).

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A Writing Aid for Synchronous Binary Access Methods (Like Some BCIs)

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Introduction: A BCI may produce above-chance performance in the lab, but harnessing it for free spelling is a challenge on quite another level—often practically impossible, unless accuracy is very high. The *Once For Yes* spelling app is designed to narrow this gap. It is optimized for binary access methods in which “yes” and “no” responses are (a) equally difficult or time-consuming for the user to produce, (b) synchronous, and (c) potentially noisy.

Material, Methods and Results: A letter- and word-prediction model runs on the user’s computer. An interface app runs on a communication partner’s mobile device. The two communicate securely via an Internet server. The system is designed to keep a human communication partner in the loop. The partner stays face-to-face with the user, judges when they are ready to be asked a question, reads out the question, cues the user to answer, and can even (optionally, depending on the access method) key in the answer. This approach avoids the Midas-touch and on-off problems, maximizes compatibility, and fosters social contact. Meanwhile, the language model assists the partner by supplying optimal questions, which may offer a candidate set of letters, a final choice of letter, or a word completion—in all cases, aiming to maximize information gain by making “yes” and “no” equiprobable given the preceding text. Optionally, the letter-prediction model can be discarded and a familiar row/column letter-board can be encoded via the same question/answer interface, although this makes information gain very suboptimal and is much less robust to noise in the user’s yes/no response, as the simulation results of Fig. 1 show.

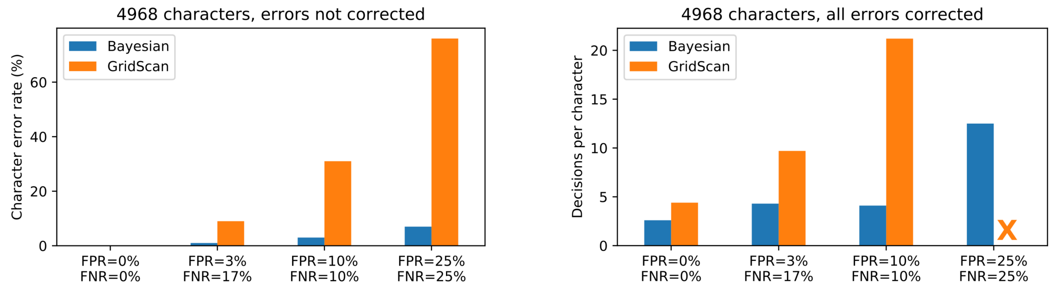

Figure 1. Simulated copy-spelling of the first 9 paragraphs of “To Kill A Mockingbird” using binary access methods with four different combinations of false positive rate.(FPR) and false negative rate (FNR). The Bayesian variant aims to maximize the information gain at each yes/no decision, whereas the GridScan method encodes the row/column selections of a static letter-board without letter prediction (both variants offer word completions where appropriate). Grid scanning is much more sensitive to noise in the access method, both in terms of character error rate when errors are left uncorrected (left panel) and the average number of decisions necessary per character when errors must be corrected (right panel). When the access method is only 75% accurate, grid-scanning produces errors more frequently than it can correct (marked X).

Discussion: An adaptive information-maximizing binary speller is much more robust, and requires fewer items to be held and manipulated in working memory, than grid scanning. It may however be perceived as more “complicated” simply because its format is unfamiliar. The relative cognitive load of the two modes remains to be quantified. The adaptive approach is likely to be *less* suitable than scanning if the user’s “no” signal is merely the absence of a response and their “yes” response can be produced asynchronously with precise timing.

Significance: This approach may bring free spelling within reach of BCI users (and other AAC users) whose access methods have hitherto been too noisy.

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BCI Performance is Influenced by Motor Imagery Strategy and Somatotopic Constraints

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Introduction: Intracortical brain-computer interfaces (BCIs) enable people with paralysis to regain function by providing control of prosthetic limbs and computer systems [1]. BCI implants often target the "arm and hand" region of the primary motor cortex to extract neural activity patterns associated with reach and grasp. The first two participants in our study (P1 and P2) successfully used reach-related imagery to control both a computer cursor and a robotic prosthetic arm. However, the third participant (P3) has experienced unusual difficulty using reaching-related imagery for BCI control despite good signal quality. In contrast, P3 has achieved dexterous control in BCI tasks involving imagined movements of individual fingers on the hand [2]. Here we explored how motor imagery-based BCI performance is influenced by the location of intracortical arrays within motor cortex, specifically with respect to the hand-knob area.

Material, Methods, and Results: Intracortical data was recorded from two intracortical microelectrode arrays (Blackrock Microsystems, Inc.) while participants imagined performing simple hand, wrist, or shoulder movements. The electrode arrays were implanted in the anatomical hand knob region of motor cortex (M1) for P3, while P2 had one implant in the hand knob area and another more medial, where shoulder-related activity would be expected. Neural firing rates were estimated from the multiunit recordings on each channel and a channel was considered modulated for a specific movement if the mean firing rate during movement was significantly different from the baseline (resting) period.

Both participants had modulated activity during attempted hand, wrist, and shoulder movements, but a greater proportion of P2's significantly tuned channels were tuned to shoulder movements (45 out of 69 tuned channels, or 65%) compared to P3's (37 out of 131 tuned channels, or 28%). Conversely, P3 more grasp-modulated channels (23 out of 69, or 33%) displayed compared to P2 (88 out of 131, or 67%) displayed). Based on these results, we had P3 re-attempt a 2D cursor center-out task using a more distal, wrist-based imagery strategy (i.e. similar to controlling his wheelchair joystick) as compared to the previously unsuccessful strategy of using shoulder-based reaching movements. Immediately upon attempting this new imagery, P3 was able to successfully complete over 90% of center-out task trials, completing 54/56 trials of an 8-target version of the task with a click component modulated by imagined hand grasp within the same session. Offline, we trained a decoding model using only one of the arrays at a time to determine if array location impacted the type of motor imagery that could be decoded. When using reach imagery, removing information from the medial array (containing more shoulder-tuned channels in both participants) had a more negative impact on decoder performance than removing the lateral array for both participants, supporting the idea that natural somatotopy places constraints on the type of motor imagery that will lead to successful BCI control.

Discussion: Despite recent human studies showing that activity in the "arm and hand" region of motor cortex is modulated by movements ranging in origin from the mouth to the feet, we found evidence of somatotopic organization influencing BCI control. Based upon these fundings, we found that BCI performance could be improved by changing the motor imagery strategy used for control.

Significance: While additional training and practice may enable successful BCI control using a variety of imagery strategies, our results suggest that using somatotopically-congruent imagery can provide an immediate performance advantage.

Acknowledgments: Research reported in this publication was supported by the National Institute of Neurological Disorders and Stroke of the National Institutes of Health (Award Number R01NS121079).

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Neurofeedback for increasing sense of presence in Virtual Reality

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Introduction: Sense of presence in virtual reality (VR) is the subjective feeling of being there. Studies [1, 2] have found that decreased parietal alpha in scalp EEG (i.e. increased activity in the visuospatial processing areas) was related with higher spatial presence. In two studies we describe (1) a high density parietal alpha neurofeedback (NF) training and (2) its adaptation into an immersive VR neurofeedback training.

Material, Methods and Results: During the high-density study (1), 15 participants were trained in 10 parietal alpha NF sessions using 128ch EEG. The output variable used was dB transformed power spectrum density (PSD) at electrode Pz and frequency band (8.5 to 12.5Hz) after current source density spatial (CSD) filtering. Feedback was presented on a monitor as a real-time bar feedback using a 2s sliding window, normalized using a session-wise 3min baseline using 1.96 standard deviation of the mean as min and max. Artifacts detected via threshold were presented as a red bar next to the feedback. Preliminary results showed that during the last session 8 participants were above chance and 5 could be considered as “BCI efficient”. After reducing to a subset of 9 channels (3 frontal, 6 parietal), 4 participants were still “efficient”. In the VR study 10 participants were trained across 5 sessions using the reduced 9ch subset. Sponge electrodes connected to a LiveAmp (Brainproducs GmbH), were placed on the parietal area below a HTC Vive pro head mounted display (HMD). In two virtual scenes developed by VTPlus GmbH, participants respectively performed controlled NF via a classical bar feedback projected on a virtual wall, then controlled the upwards flow of a 3m vertical garden fountain, respectively baselined for 1.5 min. Preliminary results indicate less participants above chance level in alpha modulation. Results were more unstable using CSD spatial filters online and offline compared to average parietal PSD recomputed offline.

Discussion: The first study showed that parietal alpha training was achievable for most participants after only a few NF sessions. Despite mixed results in the second study, the fountain NF appear comparable to the bar feedback. The combination of HMD and EEG cap generate noise and artifacts. Using CSD with reduced and noisier channels (sponges) may also have degraded the output PSD. Hence, simply averaging parietal electrodes shows better and more consistent results despite not being trained directly. Finally, participants should have substantially more than 5 training sessions for NF learning to occur.

Significance: Our studies are meant to integrate NF experience in an immersive VR treatment protocol for patients with chronic pain. VR scenarios and quick-setup ergonomic EEG-HMD equipment may be further used for different experimental and therapeutical protocols involving different neurophysiological signals.

Acknowledgements: The study is part of the research consortium VirtualNoPain, funded by the BMBF in the medical technology funding initiative (FKZ: 13GW0343). VTPlus GmbH and Brain Products GmbH are both partners in this consortium.

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The Spatial Resolution of Artificial Touch Via Intracortical Microstimulation and its Neural Determinants

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Introduction: When we interact with objects, tactile signals from the hand convey information about the objects and our interactions with them. A basic feature of these interactions – the location of object contact on the hand – is typically only available via the sense of touch because vision of the contact points is occluded. Even when visual feedback is available, it is a poor substitute for the exquisite resolution of the tactile system. Signaling contact location via bionic hands leverages the apparent labelled line coding of location in somatosensory cortex (S1). Delivering current through an electrode in S1 evokes a touch percept that is experienced at a specific location – the electrodes projected field (PF) – and is hypothesized to be determined by the electrode's location on the somatosensory homunculus. Force sensors on the bionic hand can then drive stimulation through electrodes in S1 that evoke sensations on the corresponding location on the phantom or deafferented hand, thereby intuitively conveying information about contact location. The objectives of the present study were to quantitatively characterize the stability of PFs over time and the degree to which PFs tile the hand. In two participants with tetraplegia and residual sensation in their hands, we also assessed the degree to which the PF of an electrode coincided with its receptive field (RF), defined as the patch of skin that activates neurons around the electrode tip.

Materials, Methods, and Results: Over the span of years, participants reported where on the hand they experienced a touch percept when stimulation was delivered through each of 64 electrodes in S1. We also measure the receptive fields (RFs) for the neurons recorded on each electrode by assessing the areas of skin where mechanical stimulation evoked spiking activity. We found that PFs were distributed across the hand and followed the expected somatotopic organization, with some local deviations from this pattern. PFs tended to remain on the same finger pad over the testing period but their area and center of mass varied across testing sessions (on average 3 mm). The PF of an electrode tended to be smaller than but largely subsumed by its RF, consistent with the labelled line hypothesis.

Discussion and Significance: While PFs are stable over time, they vary over a range (0 - 12mm), which will ultimately set a limit on the spatial resolution of artificial touch. The PF of an electrode is largely determined by its RF, consistent with the labelled line hypothesis of touch localization, wherein the spatial pattern of activation on the homunculus – whether by touch or by electrical stimulation – determines the location of the evoked touch sensation.

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Decoding Visual Scenes from Visual Cortex Spikes Using Deep Learning

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Introduction: Neural decoding has co-evolved in recent years the arrival of CMOS-fabricated electrophysiology probes (1) and miniaturized neural amplifier chips (2), both of which have enabled large scale neural recording. Machine learning-based neural decoding has shown incredible feats in recent years (3); namely, the decoding of: spatial coordinates of a rodent using hippocampal place cells, and motor activity (4). We explore the utility of deep learning in decoding images from neural spikes using various decoding time bin protocols, as well as across cortical and subcortical regions of the rodent brain.

Materials, Methods and Results: Electrophysiology recordings and stimulus presentations were obtained from the Allen Institute for Brain Sciences Visual Coding: Neuropixels Dataset using the AllenSDK. Three deep learning models were trained on spike counts across thousands of cortical and subcortical neurons and over 5,000 natural scene stimulus presentations. Models were tested on held-out test spikes and evaluated for image decoding accuracy.

Discussion: Three machine learning models were trained to decode and classify which image was shown to the animal solely from visual neural spiking activity. Each model's decoding accuracies were subsequently compared across various time bin durations and anatomical regions of the mouse visual system. In our analysis, time bin durations of 50 ms and greater appeared to capture neural information in the most robust way for decoding. Deep neural networks outperformed shallow neural networks and linear support vector machines across most conditions. These findings suggest possible avenues for future visual neural decoding efforts and offer insights into optimal neural decoding algorithm design.

Significance: While conventional neural decoding algorithms suffer from having to make assumptions about the encoding of neural representations, deep learning based neural decoding makes few assumptions. However, most of this deep learning-based decoding work has been done in motor cortex decoding. Accurate decoding of electrophysiology signals from brain structures involved in visual processing hold great promise in better informing our understanding of sensory processing, artificial intelligence, and BMIs for visual prosthetics.

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Spectral features of EEG signals recorded from a Stentrode in human motor cortex

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Introduction: The Stentrode is a novel brain-computer interface (BCI) technology that is implanted endovascularly to measure electroencephalography (EEG) signals from the primary motor cortex. The Stentrode records field potentials, similar to intracranial electroencephalography (iEEG), although the features of these novel EEG signals have yet to be characterized fully in humans.

Methods: The Stentrode BCI system comprises an array of 16 electrodes placed on a self-expanding vascular stent[1]. To date, seven participants with severe paralysis from amyotrophic lateral sclerosis (ALS) have been implanted with the Stentrode BCI system in 2 pilot clinical trials in Australia (n = 4) and the United States (US, n = 3). Here, we present results from the first participant in the US-based trial.

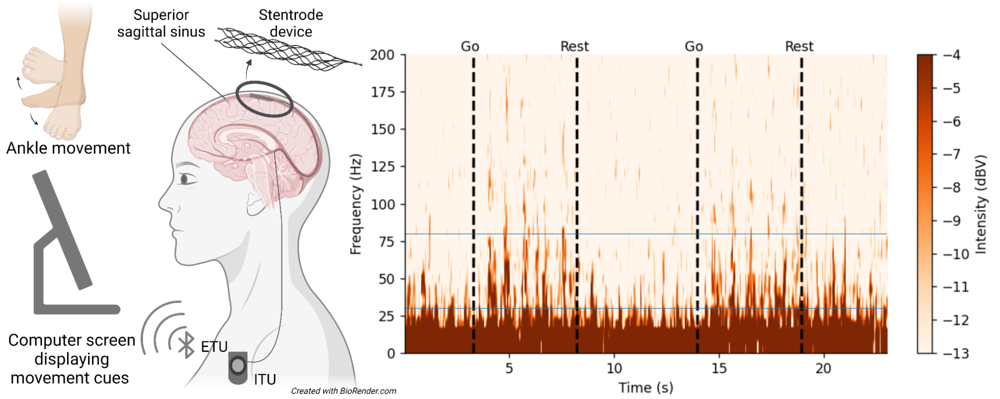

Figure 1: Schematic representation of the Stentrode implant and experimental setup. Example spectrogram for a single channel and 2 trials: The black dashed lines represent each trial (movement and rest cues). The blue lines represent the gamma frequency band where the difference between go and rest is evident.

A series of motor mapping experiments were performed to identify EEG signals that modulate with participant's attempts to move their ankles. Participants were visually cued to perform a series of 5 attempted movements in each trial. Rest periods of 5 $\pm$ 1 seconds were interleaved between trials. Here, we analyzed the EEG signals from the first US participant to identify spectral features that exhibited significant modulation during the attempted movements, as such features could be decoded to operate the BCI. We also quantified the signal-to-noise ratio (SNR) across different frequency bands. The SNR was calculated as the ratio of the mean power in each band between the movement (signal) and rest (noise) intervals.

Results and Discussion: The spectrogram in Figure 1 shows the time-frequency characteristics for recordings from a single electrode across 2 trials of attempted bilateral ankle movement. The spectrogram shows an increase in power within the beta (12-30 Hz), gamma (30-80 Hz) and high gamma (>80 Hz) frequency bands during attempted movement. The SNR was highest for the gamma gand (2.73 $\pm$ 0.07 dB), while the SNR for the beta band signal was 1.87 $\pm$ 0.06 dB. The SNR for the high gamma band signal was 1.50 $\pm$ 0.02 dB. Future work will examine the SNR across days to evaluate stability of the motor signals and identify robust and reliable features and decoding methods for performing digital communication and computer access tasks.

Significance: Following the successful completion of the first-in-human trial of the Stentrode BCI in Australia, clinical trials are now underway at 2 sites in the United States. Feature engineering is crucial for ensuring that the novel EEG signals measured by the Stentrode are classified accurately and reliably. The results reported here identified motor signals in beta, gamma, and high-gamma bands that may be useful for decoding motor intent.

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Continuous mental state estimation using EEG band power time series predictions.

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Introduction: Long Short-Term Memory network (LSTM) [1] can be used as a prediction model that reproduces time series dynamics based on training data. Here, LSTM was used to predict changes on EEG band power time series (BPts) trained with data from two different mental tasks, assuming that BPts dynamics should differ between the two tasks. Prediction error was used as a single feature to identify mental state continuously.

Methods: The EEG signals were obtained using Mental Calculation paradigm (15 subjects) over the frontal, parietal, occipital, central, and anterior-frontal regions (10-20 system) [2]. Three sessions on different days were carried out. The experimentation consisted in the alternated realization of basic arithmetic mental calculations and resting periods [3]. BPts was calculated using Power Spectral Density (PSD) over the β ([14–35] Hz) and γ([35–100] Hz) bands, assessed using the Welch periodogram method over 18 channels. Two LSTM were trained independently with BPts derived from EEG mental calculation sections ($BPts_{ac}$), and EEG rest sections ($BPts_{rest}$). Thereby, two prediction models feeding with test BPts data, produce two error signals, calculated by Mean Absolute Error (MAE). Training data was made with all information available in two of three sessions and tested over the remaining session. Area under ROC curve was used to evaluate mental state estimation.

Results: Mean population shows: the model trained with $BPts_{ac}$ over β band achieved **0.602 ± 0.025** AUROC values, whereas $BPts_{rest}$ model achieved **0.548 ± 0.022**, where 88 of 114 realizations had AUROC values below 0.5. Fig. 1 shows an example of error series and the correlation index between predictions and test BPts.

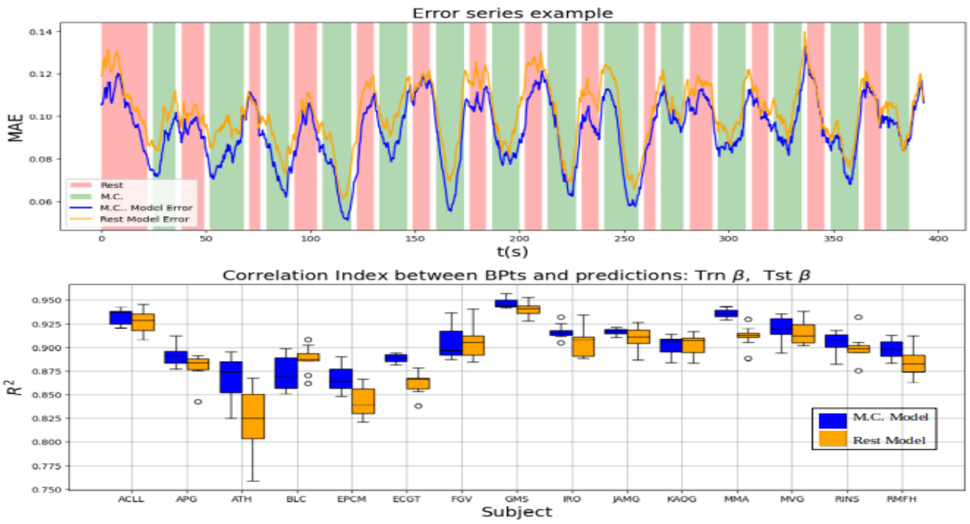

***Figure 1**.. Top: Error series, where green bands are Mental Calculation (M.C.) sections, and red bands correspond to Rest sections. Blue line is M.C. model error; orange line is Rest model error. Bottom: Correlation Index (R^2) between test BPts and predictions*

Discussion: Results suggest that LSTM prediction models could work for identifying mental state training with $BPts_{ac}$. Nevertheless, more tests are needed to find ideal LSTM parameters, channels and bands combinations. The model trained with $BPts_{Rest}$, shows a similar dynamic than $BPts_{ac}$ model, so, the error series seems to be non effective for Rest periods estimation (produced improper ROCs), but it's still useful for a binary decision. One possible explanation for this issue is that the Rest state on M.C. paradigm is not stable, that is to say, there is no explicit task in those periods, hence EEG activity does not have the same characteristics in every Rest section.

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Transitional Gestures for Enhancing ITR and Accuracy in Movement-based BCIs

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Introduction: BCIs using imagined or executed movement enable subjects to communicate by performing gestures in sequential patterns. Conventional interaction methods have a one-to-one mapping between movements and commands [1] but new methods such as BrainBraille [2] have instead used a pseudo-binary encoding where multiple body parts are tensed simultaneously. However, non-invasive BCI modalities such as EEG and fNIRS have limited spatial specificity, and have difficulty distinguishing simultaneous movements [3]. We propose a new method using transitions in gesture sequences to combinatorially increase possible commands without simultaneous movements. We demonstrate the efficacy of transitional gestures in a pilot fNIRS study where accuracy increased from 81% to 92% when distinguishing transitions of two movements instead of two movements independently. We calculate ITR for a potential transitional version of BrainBraille, where ITR would increase from 143bpm to 218bpm.

Material, Methods and Results: Our pilot study was run on two participants: one male 25-year-old and one non-binary 21-year-old. The study was run using the NIRx NIRSport, a wearable fNIRS system containing 39 optodes in a custom configuration. Participants tensed their left hand first, then their right hand and vice versa in a random order for 40 trials each. We identified the 10 most significant channels using a GLM, applied a 0.09Hz third-order low-pass Butterworth filter and then performed independent component analysis. Using a support vector machine, classification in left vs. right obtained 81% accuracy while left-to-right vs right-to-left obtained 92% accuracy.

Next, we applied the transitional gesture method to BrainBraille. BrainBraille maps different body parts onto Braille characters (Figure 1) for high speed text entry [2]. BrainBraille's prior reported ITR is reduced due to the constrained dictionary for increasing accuracy, so we consider the results without the dictionary, 143bpm at 87% accuracy. Whereas BrainBraille selected 27 out of a maximum 2^6=64 commands to ensure no more than 3 body parts were activated at the same time, transitional BrainBraille can permutatively reach up to P(6,3)=120 commands with same constraints, achieving 218bpm even when accuracy is kept constant.

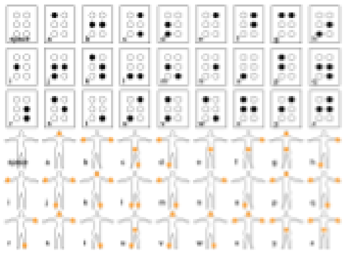

Figure 1. BrainBraille layout mapping characters to body parts for movement-based text entry.

Discussion: While gesture sequences in transitional gestures allow more commands, they may also last longer than traditional gestures due to multiple movements. However, this effect may be the reason for the accuracy benefits as it results in multiple spikes or waves in hemodynamic signals. As we run a complete study of transitional BrainBraille, we expect the effects to become clearer.

Significance: We showed that transitional gestures can be integrated into existing movement-based BCI communication methods to increase the accuracy of responses and convey information at faster rates with a greater range of commands. Our method will help advance new movement-based interaction techniques for BCIs that are faster and more reliable.

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A dynamic spiking data simulator for iBCI development

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Introduction: Development of intracortical brain-computer interface (iBCI) systems is difficult because the behaviour of the system depends on its interaction with the iBCI user. Thus, new iBCIs undergo costly continuing development post-implantation. We created Spiking Data Simulator (SDS) – a tool that generates realistic intracortical brain signals that respond to changing task demands – to facilitate robust iBCI system development early in the product lifecycle.

Material, Methods and Results: SDS (Fig. 1) is a Python package with independent modules that interact with each other and with clinical BCI systems (e.g., Blackrock Neurotech's Neuroport system). The SDS Simulator module consumes behavioral state and produces neural activations via a generative model; SDS includes pre-trained models (e.g. a tuning curve model [1]) trained on publicly available data [2] and instructions to train and substitute a custom model. The SDS Signal Output module consumes simulated neural activations and produces realistic raw brain signals including field potentials and multi-unit spiking. The SDS Examples module provides tools to help the iBCI developer complete the loop.

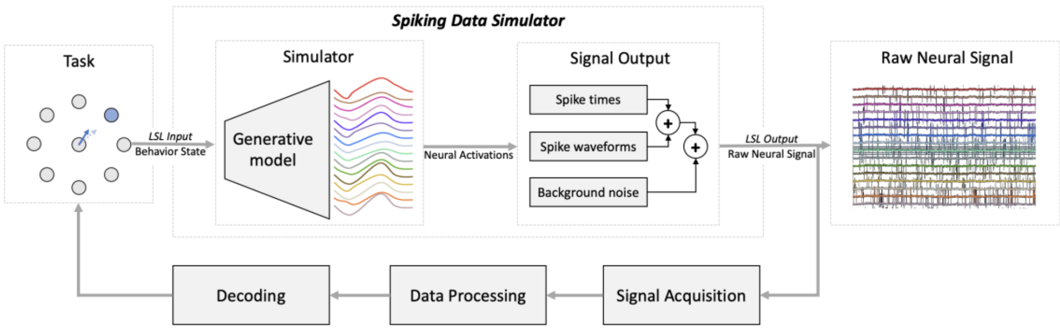

Figure 1. *Spiking Data Simulator system diagram.*

SDS ran at about 30% CPU utilization on an i3-12100f while generating 190 unique channels of data with 30 kHz sampling rate. The duration between reception of application state update and publishing the associated raw signal change was 1.23 +- 0.37 msec. Generated signals' statistics were reproducible when receiving the same state timeseries, and were similar to recorded brain signals.

Discussion: SDS generates realistic and dynamic brain signals that modulate in response to ongoing task demands. SDS is designed to be modular and easily extended; future extensions may add latent-space perturbations, non-stationarities, and support for additional neurophysiology platforms.

Significance: The SDS can serve as a surrogate participant to facilitate end-to-end iBCI development and testing prior to deployment, with potential to decrease costs, and improve system acceptance and success.

Acknowledgements: We thank Blackrock Neurotech for the support integrating SDS with their platform.

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Cross-Task Transfer Learning in Emotion Estimating BCI

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Introduction: In the machine-learning literature, "transfer learning" often refers to cross-subject learning. In this type of transfer learning, data from other participants is used to build a classifier or model new participants. Cross-subject transfer learning has been applied for emotion estimation in the field of Brain-Computer Interface (BCI). However, cross-subject transfer learning requires a large dataset. To overcome this limitation, we implemented cross-task transfer learning, which, to our knowledge, has not been used yet in affective BCI. Here, we used a unique data-set with three different types of emotion elicitation stimuli to test this cross-task transfer learning.

Material, Methods and Results: The dataset consists of three different types of stimuli: pictures (International Affective Picture System), facial images (Pictures of Facial Affects), and music. Each stimulus was active for 15 seconds. Participants rated each stimulus on three emotional dimensions (valence, arousal, and dominance) using a 5-point Self-Assessment Manikin [1]. Twenty participants performed this study and each experienced a total of 240 stimuli. EEG data were recorded using a 64-channel Cognionics system with a sampling rate of 500 Hz.

We calculated the magnitude-squared coherence estimate (MSCE) between all 64 channels as input features and performed t-tests as a feature selection method. A binary classification was performed with a threshold of 3 in each emotional axis, using a simple tri-layer neural network (5-fold cross-validation). Here, we tested two different approaches: - in-task classification and cross-task classification. We computed balanced accuracy and its credible intervals to evaluate the performance against chance [2]. Bonferroni correction was applied to set the significance level at $\alpha/2$ for in-task classification (2 emotional axes per dataset) and $\alpha/18$ for cross-task classification (18 total comparison), where $\alpha=0.05$. Also, we performed a statistical comparison between the balanced accuracies of cross-task and their corresponding test set's in-task accuracy for both valence and arousal axis after Bonferroni correction (at the significance level of $\alpha/12$).

In Table 1, the diagonal elements represent the average balanced accuracy of in-task classification and the off-diagonal values indicate the average balanced accuracy of cross-task classification for each axis. The average in-task balanced accuracies are higher than the cross-task balanced accuracies except in three cases. For the valence axis, no significant differences were observed between in-task and cross-task performance. For arousal, none of the differences survived Bonferroni correction ($p < 0.0042$), and only the reduction in performance on POFA by training on Audio would have been significant without the correction ($p = 0.035$).

Table 1: Mean balanced accuracies for all participants of both in-task and cross-task classification

Valence					Arousal			
Train \ Test	IAPS	POFA	Audio		Train \ Test	IAPS	POFA	Audio
IAPS	**53.92***	56.25*	52.24		IAPS	**60.88***	62.04*	59.424*
POFA	52.18	**57.04***	53.33		POFA	63.06*	**69.69***	61.31*
Audio	51.85	53.2	**52.19**		Audio	59.23*	60.05*	**63.33***

*The lower bound of the credible interval is above chance.

Discussion & Significance: This study preliminary exhibits the effectiveness of cross-task transfer learning in BCI emotion detection. Cross-task transfer learning is performing well for the arousal axis since the lower credible boundary is always above chance for all cases. However, the performance of cross-task transfer learning is not satisfactory for the valence axis.

Acknowledgements: This study is supported by NSF under award #1910526. Findings and opinions within this work do not necessarily reflect the positions of the National Science Foundation.

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Novel EEG Network Neuroscience Features for Dementia and Awareness Level Estimation in Passive BCI Framework

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Introduction: We report pilot study results of novel EEG features utilizing the latest tools from network neuroscience [1] with possible application to early onset dementia neuro-biomarkers within a digital non-pharmacological therapy (NPT). Network analysis of EEG time-series allows for awareness level estimation [1] from a resulting network graph of node and edge numbers. We present statistically significant (see Figure 1) differing network node and edge number distributions between two groups of healthy aging and MCI evaluated (MoCA$\leq$ 25) conducting passive BCI experiments using FastBall paradigm [2]. The results reported in Figure 1 indicate different awareness levels in MCI elderly participants [1]. The pilot study was conducted using a Unicorn EEG headset at the Nicolaus Copernicus University in Torun, Poland. The Institute of Psychology UNC Ethical Committee for Experiments with Human Subjects has approved the study.

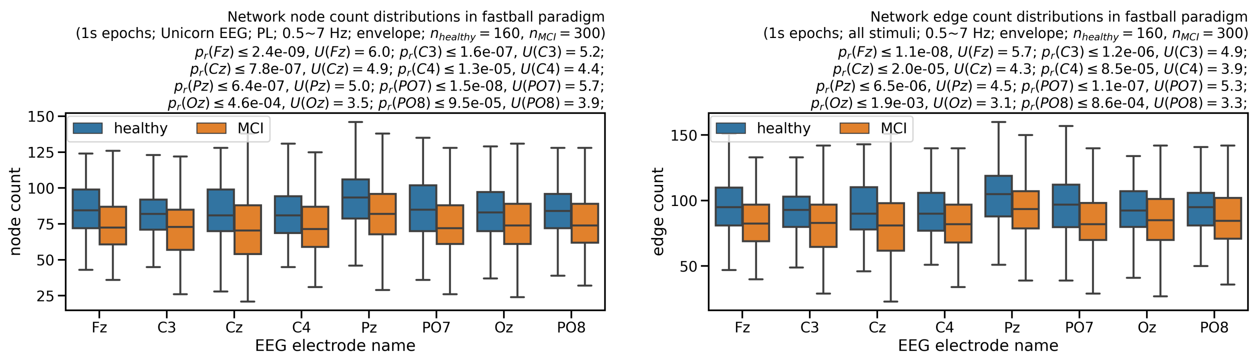

Figure 1: Boxplots with marked median, quartile ranges, and whiskers extending to show the remainder of the distributions of the network signal analysis resulting in node and edge counts for MCI versus healthy aging cognition subjects for all EEG electrodes analyzed separately (Unicorn EEG headset) during FastBall paradigm [2] with 5 Hz carrier/RSVP frequency. All electrodes resulted in significantly smaller node and edge numbers' distributions for the MCI-evaluated elderly participants ($p_r \ll 0.01$).

Discussion and Significance: The reported novel network science application to EEG time series introduces a candidate for an objective digital neuro-biomarker development within a passive BCI framework. A wearable EEG application shall allow for a plausible replacement of biased "paper & pencil" tests for a mild cognitive impairment (MCI) evaluation. Subsequent machine-learning model development and appropriate ethical supervision shall follow.

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Using a Pre-trained Neural Language Model to Make Character Predictions for Brain-Computer Interfaces

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Introduction: Because the signals acquired from a BCI user can be quite noisy, often a language model is used to assist the software in selecting the user's intended character. While traditional *n*-gram language models can provide adequate predictions and can be queried quite efficiently once trained, state-of-the-art in natural language processing typically uses a large pre-trained neural network language model such as GPT-2 [1]. In this work we explore some of the speed and accuracy tradeoffs between these two models.

Material, Methods, and Results: We used a training set of 100 phrases to test a range of parameters for our neural language model to determine the most efficient option that still provided high quality predictions. To measure the accuracy of predictions, we used *perplexity*, which describes the branching factor of the search. A lower average perplexity indicates more accurate predictions. We ran a test set of AAC-like phrases [2] through our model with the chosen parameters and through a large 12-gram model that was trained on AAC-like data [3]. We found that a GPT-2 model with 124M parameters trained on text scraped from webpages had a perplexity of 4.82 with an average prediction time of 1.72 s, while a larger GPT-2 model with 355M parameters yielded a better perplexity of 4.18, while increasing the average prediction time to 2.86 s. The 12-gram model had a perplexity of 2.47 with an average prediction time of 0.04 ms.

Discussion and Significance: Character predictions can help to improve users' typing speed and accuracy while using BCI [4]. We observed substantial differences in prediction speed and accuracy between *n*-gram and pre-trained neural language models. While this work showed that the 12-gram model outperformed the GPT-2 model in both perplexity and prediction time, we conjecture that this difference may be due in large part to the text they were trained on. In future work, we plan to adapt our GPT-2 model to AAC-like text to investigate if we are able to achieve further accuracy gains to the point where it might justify the higher prediction time. It is also possible that even larger versions of the GPT-2 model could lead to further improvements.

Acknowledgements: This work was supported by NSF Graduate Research Fellowship 2034833.

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The effect of gamified calibration environment on P300 and MI BCI performance in children

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Introduction: A major challenge with BCI use is the requirement for subject-specific training, which is often tedious and unengaging for the user, but necessary to improve efficiency [1]. This is especially true for children, who's limited attention and motivation pose pressing challenges for the implementation of BCI. Games present clear objectives with short-term goals that confer rewards and act as external motivators to provide a seamless sense of advancement [2]. Several studies have shown that the addition of scoring systems, prizes, and awards to tasks, a process known as "gamification", can increase motivation, attention, and task performance in children [3]. This randomized prospective cross-over study aimed to address this challenge by comparing the effects of gamified versus non-gamified calibration environments on classification accuracy and BCI performance on utility-driven tasks.

Materials & Methods: Thirty-two typically developing children (14 female, mean age 11.9 years, range 5.8-17.9) attended two sessions lasting between 1.5-2 hours. Two standard BCI paradigms well-established in adults were studied: spelling using visual P300 event-related potentials (P300) (3x3 T9-style speller) and cursor control using motor imagery (MI). Gamified and non-gamified calibration paradigms were generated using BCI Essentials. Research-grade EEG-based BCI systems were utilized for signal acquisition at 256Hz (g.tec medical engineering GmbH, Schiedlberg Austria). Frequency filtering was done with 5th order Butterworth bandpass filters with bands of 0.1-15Hz and 5-30Hz for P300 and MI, respectively. P300 covariance matrices were constructed with XDawn spatial filtering, the tangent space representation of these matrices was classified using linear discriminant analysis (LDA). Tangent space representations of MI covariance matrices were classified with logistic regression. The MI classifier was iteratively retrained in-session to provide user feedback. Motivation, tolerability, and mental workload (NASA-TLX) were evaluated following each paradigm.

Results: For the P300 paradigm, mean classification accuracy was 96% with both gamified and non-gamified calibration. For the MI paradigm, mean classification accuracy was 62% with gamification and 60% without gamification. Mean online BCI accuracy for the MI task was 63% for both conditions. For the P300 task, differences in online BCI accuracy were only observed below 4 flashes per row/column for both conditions. Motivation and tolerability scores across all four paradigms were high. Mean total workload as a percentage of the possible score ranged from 34-39% for the four paradigms, which is between a low-moderate workload. Females perceived gamified tasks as having a lower mental workload ($p<0.05$). There were no significant differences found between classification accuracy, online BCI accuracy, motivation, tolerability, or workload. Three children verbalized that they did not enjoy the gamified MI environment because it was frustrating. Further analysis will investigate the potential effects of age, order and factors affecting performance, such as fatigue, mood, and regular video game play.

Discussion: Our results reinforce the ability of typical children to control advanced BCI systems with performance comparable to adults. Gamified calibration environments may not enhance BCI classification and performance in children. It is possible that the gamified environments utilized in this study were not engaging enough.

Significance: To our knowledge, this is the first study that investigates the effects of gamified calibration paradigms on classification accuracy and BCI performance in children. Future research on optimizing BCI training paradigms for children is necessary for implementation of BCI in this population.

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Design and evaluation of a tangible and haptic brain-computer interface for upper limb rehabilitation after stroke

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Introduction: The French ANR GRASP-IT project aims to recover upper limb control by improving the kinesthetic motor imagery (KMI) generation of post-stroke patients using a tangible and haptic interface [1] in a gamified Brain-Computer Interface (BCI) training environment (Fig. 1).

Material, Methods, and Results: This innovative KMI-based BCI integrates complementary interaction modalities such as tangible and haptic interactions. We designed and tested usability (including efficacy towards the stimulation of the motor cortex) and acceptability of this multimodal BCI.
The GRASP-IT project designed a gamified non-immersive virtual environment to support four hand motor imageries (grasp, pinch, realize, rotate) in 16 everyday situations.

Discussion: This multimodal solution is expected to provide a more meaningful, engaging and compelling stroke rehabilitation training program based on KMI production [2].

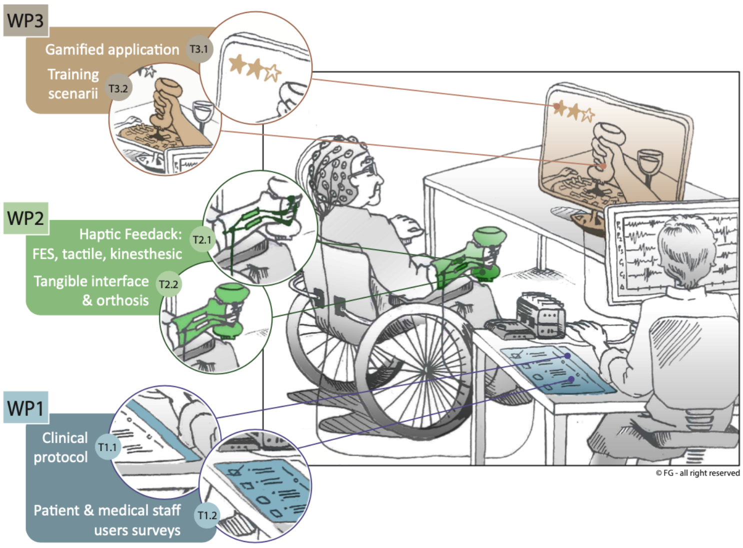

***Figure 1.** Scheme of the project structure*

Significance: The project will integrate and evaluate visual, tangible and haptic neurofeedbacks integrated in a 3D printable flexible orthosis in the gamified multimodal BCI in an ambitious clinical evaluation with 75 hemiplegic patients in 3 different rehabilitation centers in France.

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Does my child know I'm here? EEG signatures of parental comfort for disorders of consciousness in critically ill children

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***Introduction**:* Every day in the Pediatric Intensive Care Unit (PICU), children suffering from severe brain diseases lie unconscious and comatose. Parents lie beside them, desperately wondering if their child will ever awaken. Many patients suffering from coma and related disorders of consciousness (DoC) show no clear physical behaviours of conscious awareness but have residual cognitive function. This cognitive-motor dissociation (CMD) can be seen by the presence of volitional brain activation to motor commands via EEG[1]. CMD occurs in up to 20% of adults with DoC[1], has high early prognostic value for predicting good outcome[1] and can be used by brain-computer interfaces (BCIs) to create simple communication ("Yes"/"No") systems for locked-in patients[2]. Despite such potential, children have been entirely neglected from CMD and BCI research[1,3]. Our group has shown that children (even those with severe brain disorders) can operate many BCI systems with comparable success to adults[2], including one built for DoC in adults[1,2]. Children's developing brains may also harbour unique, robust networks elicitable by simple stimuli not found in adult brains such as the response to parental comfort and affection[5]. Detecting the activation of such networks in comatose children whose parents are constantly caring for them at their bedside could reveal new brain activity markers. These may then predict clinical outcomes early on, and possibly allow families to communicate with their child in the most critical of circumstances. To explore this possibility, the present preliminary case study aimed to identify EEG signatures of parental comfort in a child with acute DoC.

***Material, Methods, and Results**:* 17 hours of video/EEG data was obtained via the Alberta Children's Hospital Neurocritical Care program for a 13-year-old female patient afflicted with DoC following traumatic brain injury (inclusion criteria searched: age 6mo-17yr; acute encephalopathy with Glasgow Coma Scale score < 6; 24+ hours of video/EEG monitoring). Blinded video review defined three clinical states: parental comfort (physical contact / talking to child), parent presence (in room only), and parent absence. Video states were time-locked with recorded EEG (bandpass-filtered [0.1 – 40 Hz], cleaned [removal of artefacts, periods of status epilepticus, etc.], downsampled [256 Hz]). The Highcuhi Fractal Dimension (HFD), a complexity measure recently reported as a sensitive discriminative marker of severity in EEG analysis for DoC[4], was computed for 1 sec. epochs and standard 20 channels. Results were clustered and visualized via K-Means / t-SNE, to identify the most dynamic sections of recorded EEG. Clusters were mapped to clinical states defined in the video (parent presence/absence).

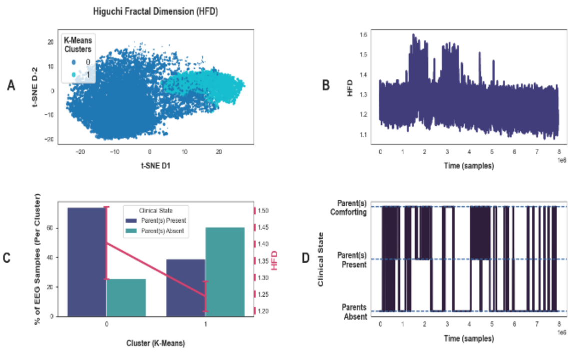

Fig.1. **A:** K-Means clustering indicated two clearly separable clusters of HFD values (Silhouette score = .54) – visualized via t-SNE. **B/D:** Visual comparison of HFD changes (**B**) with changes in video-defined states (**D**) over time suggested similar trends. **C:** Mapping the video labels (parental presence/absence) and mean HFD across channels to the two identified clusters indicated differences in both values; higher HFD (1.40 ± .11) and times of parental presence (74% of clustered points) were prevalent in cluster 0, whereas lower HFD (1.24 ± .05) and parental absence (61%) tended towards cluster 1.

***Discussion**:* Preliminary results suggest that parental comfort in the ICU may elicit detectable changes in EEG-measured brain activity of children with acute DoC, which may indicate some intact cognition and/or a potential marker for prognostication and building BCI-based communication systems in these contexts.

Significance: Developing biomarkers for DoC in children is essential for reconnecting them with their families; future studies can now test the HFD and other EEG features for prognostic and communicative utility in this context.

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NeuroExo: A Low cost Non Invasive Brain Computer Interface for upper-limb stroke neurorehabilitation at home

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Introduction: The use of scalp electroencephalography (EEG) signals for brain-computer interface (BCI) to control end effectors in real time, while providing mobile capabilities for use at home neurorehabilitation, requires of software and hardware robust solutions. Moreover, to ensure democratized access to these systems, low cost, interoperability, and ease of use are essential. These challenges were addressed in the design, development and validation of the NeuroExo BCI System. As a proof of concept, the system was tested with an exoskeleton system for upper-limb stroke rehabilitation as the end effector.

Material, Methods and Results:

- Headset Design and Development**:** a one size-fits-most five dry comb electrodes EEG headset was developed based on the initial pilot study of [1, 2], where a BCI-exoskeleton system for upper-limb stroke rehabilitation was demonstrated in stroke survivors.

- BCI Design**:** BeagleBone Black – Wireless (BBB) was selected as the processing unit, while ADS1299 and ICM-20948 were the amplification-filtering-ADC and IMU (3-axis accelerometer and gyroscope) devices, respectively. LabVIEW (National Instruments Inc.) was chosen as the primary coding language.

- At-home validation of the BCI system in individuals with chronic stroke**:** In closed loop BCI operation, a WiFi-enabled robotic arm for upper-limb rehabilitation was used as the end effector. In this test, the system interacts with the participant in real time using a user-specific trained machine learning model for intent detection. The system will be demonstrated at this BCI meeting.

Discussion: The development of the proposed system went through a concurrent evolving of its parts to achieve interoperability, usability, and reliability. Similar endeavors would need to have this in mind to avoid expensive redesigning in late stages of the project.

Significance: This system fosters the democratization of BCI systems for applications beyond clinical rehabilitation including, but are not limited to, robust BMI control, IoT, video games, more engaging learning environments, and attention tracking to name a few application domains.

Acknowledgements: This work was supported in part by NSF PFI Award # 1827769.

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You've got mail: using telehealth to improve dissemination of brain-computer interfaces (BCIs) for communication and control.

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Introduction: Despite successful independent home use of BCIs (e.g., [1,2], they remain largely unavailable to the people who need them most[3]. We are exploring the use of telehealth to introduce clinicians, patients, and their caregivers to BCI technology in the form of a simple one-target SSVEP-based BCI demonstration application. The goal is to encourage and facilitate adoption of an EEG-based BCI for important communication and control functions.

Materials, Methods, Results: Two people (S1, S2) with amyotrophic lateral sclerosis (ALS) (ALSFR[4] functional ratings of zero) and their caregivers [system operators (SO)] received information via telehealth, phone, and mail to ascertain interest and obtain informed consent for remote BCI training and support. S1 and SO1 were naive to BCI. S2 had tried a BCI in clinic and at home without success; SO2 had observed some sessions. System hardware was a laptop (ASUS A15, Windows 10), an USB amplifier (g-tec), and a cap (ECI, locations Fz, Cz, P3, Pz, P4, Po7, Po8, Oz). System software was BCI2000 (v3.6) and the SSVEP MusicBox (MB) (Psychtoolbox, MATLAB, MP3 audio files). The MB is a one-target BCI that provides visual and auditory feedback in proportion to amplitude of the steady state visual evoked potential (SSVEP) (Fig 1). Each pair (S and SO) received a hardware schema and a video of cap application and care. In telehealth visits (TV) 1 and 2, we: verified materials; supervised system assembly, cap application and care; and introduced the MB task. In TV3, the SO had applied the cap before the session began. We reviewed placement, gel application, and signal quality (e.g., ground and reference, artifacts, impedance). We then showed MB startup and carried out a full session (25 trials). SOs contacted us immediately before and after subsequent sessions. They asked questions, and we used TeamViewer software if necessary. S1 and S2 completed data collection for 3 and 5 sessions, respectively. Investigator-observed and independent sessions did not differ in signal quality (impedance) or in performance. Electrode impedances never exceeded 15 KOhms. S1 was subsequently successfully introduced to the P300-based BCI speller.

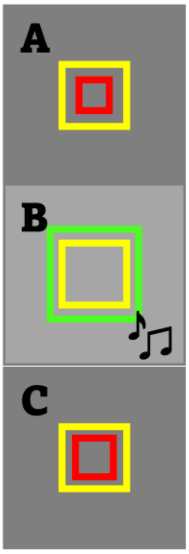

Fig 1. The laptop screen displays a single 6x6" box that flashes light (dec105) and dark (dec175) gray at 7.5 Hz. **A.** The gray box contains the outline of 2 rectangles. The dependent rectangle (DR, red) grows in proportion to the amplitude of the user's SSVEP as determined by conical correlation analysis (CCA). A static rectangle (SR, yellow) represents the set CCA threshold. **B.** When the SSVEP exceeds threshold. The DR exceeds the size of the SR, turns green and music plays. **C.** If the SSVEP amplitude drops below threshold, the DR turns red, and the music stops.

Discussion and Significance: Early and frequent exposure to high-tech augmentative and alternative communication (AAC) (e.g., a brain-computer interface (BCI)) can encourage and facilitate eventual adoption and productive use. The one-target MusicBox task and a telehealth format can introduce patients and their caregivers to BCI use. It may provide a gateway for BCI translation into standard clinical practice.

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Why BCI-fi?

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Introduction: For decades, a myriad of papers and posters have noted that BCIs are gaining attention among the public due to increased research, conferences, classes, commercial efforts, media, and other factors [1-4]. However, BCIs have also been getting attention since before the invention of BCIs through BCI-fi, which means BCI-related science fiction [2]. In addition to academic curiosity, BCI-fi merits study because it probably influences public perceptions of BCIs more than ***all other factors combined.***

Material, Methods and Results: I reviewed numerous examples of BCI-fi, articles about BCI-fi, award mechanisms for both BCI and sci-fi, and other sources. Very many BCI experts were consulted. Recurring components of BCI-fi include:

- "BCI exaggeration" is common. BCI-fi BCIs often seem unlimited by technology.
- BCIs are rarely used alone. They're often integrated with intelligent systems, perfectly immersive VR, brain stimulation, and who/what-ever they control.
- Neurotechnology enables otherwise unsafe behavior.
- BCI systems are often used by evil entities for evil purposes in an unethical society.
- Positive applications of BCIs and other technologies are minor.
- Preparation, training, and universality are usually ignored.
- Most BCI-fi is written without real-world BCI practitioners. [5] is an exception.

Discussion:
BCI-fi has been around since (arguably) 1818 [6], and is becoming more prominent across different media. BCI-fi can be fun, inspiring, and informative, but can also negatively influence public beliefs and decisions regarding BCIs.

Significance:
Laypeople often share views about BCIs with BCI experts that are based on BCI-fi – often without realizing it. Thus, studying how BCI-fi and BCI-re interact could help us understand and improve BCI development, BCI-fi and communication with the public.

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Mapping Research on Brain-Computer Interfaces for Augmentative and Alternative Communication Across the Globe

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Introduction: Due to the possibilities of improving the quality of life of individuals with different conditions and needs, an important virtue of a healthcare-related research field is to be globally far-reaching. This is even more relevant when the characteristics of the research populations might vary a lot, as in the case of studies involving persons with disabilities. Taking this into account, this investigation presents a scientometric mapping of global research on augmentative and alternative communication brain-computer interface (AAC-BCI) systems, with the goal of addressing the following question: how widespread is AAC-BCI research across the globe?

Methodology: The systematic review of research on AAC-BCI systems for individuals with disabilities written by Peters et al. [1] was used as data source for this study. The 73 articles that met the authors' inclusion criteria (cited in their Supplementary Table 1) were considered. For each of these articles, the affiliation country(ies) of each author was extracted (when an author reported being affiliated to two or more institutions in the same country, this country was counted only once). Author disambiguation was performed before data analysis, and general information about the global reach of research on AAC-BCI systems was obtained. Finally, the percentage of each country among the affiliations reported in author entries was calculated.

Results: The 73 articles contain 512 author entries (avg. of 7.0 authors per article, min. of 2, max. of 20), corresponding to 326 unique authors. These authors reported being affiliated to institutions based in 20 different countries: 13 in Europe, 3 in Asia (all in East Asia), 2 in North America and 2 in South America. Only 22 (4.3%) author entries report simultaneous affiliation to institutions in two or more countries, but 34 (46.6%) of the articles include authors at least partially based in two or more countries – showing a substantial degree of internationalization of the collaborations. However, only 2 (10%) of these countries – Ecuador and Colombia – are (partially) in the Southern Hemisphere, and the majority of them (16, i.e. 80%) are classified by the World Bank as high-income economies in 2023. Fig. 1 shows the percentage of each country among the affiliations reported in author entries, and indicates the role of institutions from the USA, Germany and Italy (respectively in 26.0%, 20.4% and 14.0% of the affiliations) for the research in the field.

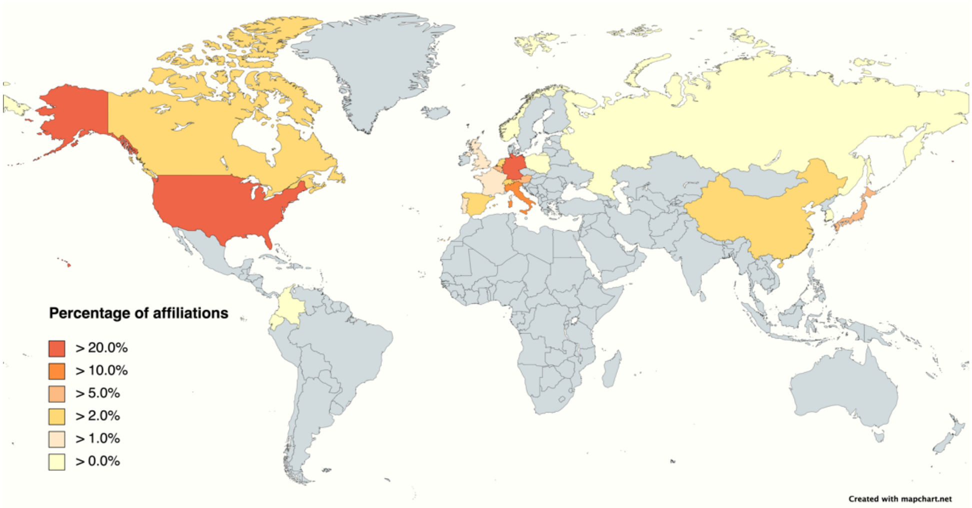

***Figure 1**. Percentage of each country among the affiliations reported in author entries.*

Discussion: The results make it clear that research on AAC-BCI systems for individuals with disabilities is still very dominated by authors based in high-income countries, especially in North America and in the European Union. The number of articles that originate from collaborations between authors working in different countries is meaningful; however, the need for collaborations that also involve institutions in the Global South is evident. This could be achieved by promoting conferences, scholarships, internships and hands-on training for researchers based in the countries underrepresented in the field, in order to increase the potential benefits that this research could bring for practitioners, students, the civil society and, above all, patients and their families in the whole world.

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Modeling local neural population responses to intracortical microstimulation.

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Introduction: Intracortical microstimulation (ICMS) is a primary tool for driving neural population activity, and may provide an avenue to create rich somatosensory percepts when delivered to the somatosensory cortex (S1) in intracortical brain-computer interfaces. However, current stimulation strategies, limited to fixed patterns of stimulation pulses, do not provide this rich feedback. These patterns can be coarsely optimized with participant reports about the evoked percepts, but this process is time-consuming and cannot be efficiently scaled to complex stimulation patterns, such as those using multiple electrodes [1]. We thus propose to characterize the evoked *neural response* as a step towards more sophisticated stimulation.
Materials, Methods, Results: We delivered ICMS trains in two participants, each of whom had two microelectrode arrays implanted in S1. During stimulation, we simultaneously recorded full bandwidth data (30 kHz) from these same electrodes using custom headstages (Blackrock Microsystems). Stimulation comprised 1-s trains of biphasic pulses; for each pulse we varied the amplitude (20-80 uA), timing (average rate 20-100 Hz), and electrodes (up to 5 electrodes in a trial) to study their effect on the recorded neural response.

We developed two models to characterize the spiking response to stimulation. First, we extracted the spiking response from the voltage recordings, which are contaminated with highly variable electrical artifacts. To do this, we created a deep network artifact estimator that re-enables spike detection within 1.3 ms of pulse offset. The observed spiking responses were diverse across stimulation parameters, consistent with previous studies on more limited stimuli [2]. Next, we developed a separate deep network model to capture the relationship between the commanded stimulation and observed response. Ablation studies confirmed that responses were affected by the choice of stimulating electrode, pulse amplitude and timing. These effects extend temporally beyond 200 ms and interact with the ongoing local population state.

Having quantified the complex neural response, we then considered practical strategies for exploring the exponentially large set of stimulation parameters. To do this, we designed a set of generalization experiments wherein models fit to one set of stimulation parameters were evaluated on trials collected with different parameters. We encouragingly find good generalization to novel pulse timing and amplitude (sampled from the same random distribution), but limited generalization to different electrodes. Finally, we find that multi-session data aggregation can potentially overcome practical performance limits in single sessions.
Discussion: We find that neural responses can be accurately modeled within practical experimental budgets. Characterization of high-electrode count stimulation remains a challenge, motivating the development of data aggregation strategies. Other next steps include developing stimulation controllers and modeling the relation between neural response and evoked percepts.
Significance: Our results lay groundwork for precise stimulation for neural population control.
Acknowledgments: JY is supported by the DOE Computational Science Graduate Fellowship. Experiments supported by NINDS NS107714 and NS123125.

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Brain Spine Interface to Restore Walking After Spinal Cord Injury

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Introduction: To walk, the brain delivers executive commands to the neurons located in the lumbosacral spinal cord. While the majority of spinal cord injuries does not directly damage these neurons, the disruption of descending pathways interrupts the brain-derived commands that are necessary for these neurons to produce walking. The consequence is permanent paralysis. Here, we hypothesized that a digital bridge between the brain and spinal cord enables volitional control over the timing and amplitude of muscle activity, restoring a more natural and adaptive control of walking in one participant with chronic spinal cord injury.

Material Methods and Results: To establish this Brain-Spine Interface (BSI), we integrated two fully-implanted systems that acquire wirelessly the electrocortical activity (ECoG), decode motor intentions in real time and stimulate the lumbosacral spinal cord to elicit the corresponding movements. ECoG implants consist of an 8-by-8 grid of 64 electrodes [1,2]. ECoG signals are sampled at 586Hz per channel. A decoding pipeline extracts temporal, spectral and spatial features embedded in the ECoG signals related to the intention to move. These features are then fed into the decoding algorithm that predicts the attempts to move the lower limbs based on a recursive exponentially weighted Markov-switching multi-linear model algorithm [3]. To support the control of lower limb movements, the outputs of the model are encoded into updates of joint-specific stimulation programs that are constrained within pre-established functional ranges of amplitudes. These commands are delivered to the spinal cord through the ACTIVA RC ® implantable pulse generator [4].

We first tested this *BSI* during voluntary elevations of the foot while standing. After only 5 minutes of calibration, the *BSI* supported continuous and intuitive control over the activity of hip flexor muscles, which allowed the participant to achieve a fivefold increase in muscle activity compared to attempts without the BSI. Similarly, up to 6 independent joint movements could be independently controlled with a single model. We provided the same configuration to support walking with crutches. The BSI enabled continuous, intuitive and robust control of walking. When the BSI was turned off, the participant instantly lost the ability to perform any step despite detected attempts to walk from the modulation of cortical activity. Walking resumed as soon as the BSI was turned back on. The participant completed 40 sessions of neurorehabilitation that involved walking with BSI, single-joint movements with BSI, balance with BSI, and standard physiotherapy. The participant exhibited improvements in all the conventional clinical assessments such as the 6-minute walk test, weight-bearing capacities, timed up and go, Berg Balance Scale, and walking quality assessed. Finally, we designed a system that could be operated by the participant without any assistance. This system includes a walker equipped with an integrated case that embeds all the components of the BSI.

Discussion: These results demonstrate that a fully implanted BSI can restore voluntary motor control over previously paralysed leg muscles. Additionally, the suggest that establishing a continuous link between the brain and spinal cord promotes the reorganization of residual neuronal pathways that link these two regions under normal physiological conditions.

Significance: This proof of concept in one human participant augurs a new era in the treatment of motor deficits due to neurological disorders. We anticipate that the approach is generalizable to a broad population of patients and could even be applied to restore upper limb function after cervical spinal cord injury or stroke.

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Transcutaneous Electrical Spinal Stimulation Fosters Motor Imagery Skill Acquisition

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Introduction: Non-invasive brain computer interfaces (BCIs) present promising solutions for patients with neuromuscular impairments allowing them control over assistive devices [1]. BCIs are commonly controlled through the imagination of limb movements — motor imagery (MI), which relies on voluntarily modulated sensorimotor rhythms (SMRs). However, a major challenge is the non-stationarity of SMRs, which require longitudinal feedback training for MI skill acquisition. There had been several approaches aimed at increasing the excitability of the sensorimotor networks and thus the quality of SMRs through incorporating electrical stimulation as feedback [2], but less focus has been given to the inhibitory circuits involved in MI. In this study we use transcutaneous electrical spinal stimulation (TESS), which has been shown to exhibit inhibitory effects on the cortex [3], prior to BCI training to promote faster and better BCI skill acquisition.

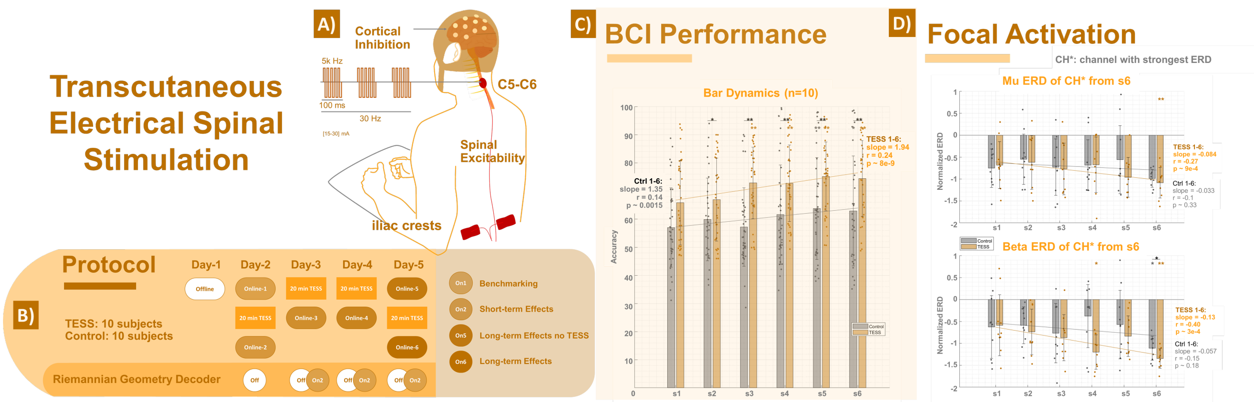

Figure 1: A) Illustration of setup, B) Protocol Design, C) Comparison of BCI performance between TESS group (orange) and Control group (grey), D) Comparison of the degree of ERD focality of the Mu and Beta bands across the two groups.

Material, Methods, and Results: Twenty healthy participants trained over 5 days to control a binary BCI (left vs right MI, Fig. 1B). Participants were randomly split in two groups, where 10 subjects received 20 minutes of TESS before each BCI session. Consistent with previous work [3], TESS was delivered at the C5-C6 level with parameters shown in Fig. 1A. After the longitudinal training, we found significant improvement in BCI performance, measured by the percentage of time participants were in control of the bar task (Fig. 1C). Notably, the TESS group had significantly better performance compared to the control starting on the second session ($p < 0.001$, n=40) until the end of training (TESS: $74.4\% \pm 13.5\%$, Control: $62.9\% \pm 19.5\%$, $p < 0.01$, n=40, LME). The performance in the TESS group was also accompanied with a statistically significant increase in focal activation in the mu and beta bands as shown in Fig. 1D.

Discussion: The BCI performance over the training sessions provide supporting evidence to the hypothesis that pre-training TESS promotes the acquisition of the MI skill and supports better BCI control. The emergence of more focal ERD patterns with TESS is consistent with the expected focal activation/surround inhibition phenomenon during MI.

Significance: In contrast to previous work, our findings highlight the role of inhibition in MI skill acquisition. We propose that using TESS to induce cortical inhibition before focally activating the motor cortex with MI promotes the acquisition of the MI skill for better BCI control. This not only has implications for replacing lost functions, but also for rehabilitation.

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Event-Related Potential to visual cues in Motor Imagery Brain-Computer Interface

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Introduction: In general, visual cues (like arrow or text) are used to instruct a subject the direction of imagery in offline data collection of motor imagery (MI) Brain-Computer Interface (BCI), while these stimuli may not be used in online MI-BCI. Such visual stimulation may introduce Event-Related Potential (ERP) in offline data, causing the difference in offline from online data. However, the existence of ERPs is not been thoroughly studied. In this study, we investigated ERPs in public motor imagery datasets.

Material, Methods and Results: We analyzed three public datasets on left- and right-hand MI to confirm the ERPs: Lee(2019) (n=54) [1], Cho(2017) (n=52) [2] and Shin(2016) (n=29) [3]. The data name is the author's last name and the publication year of the paper. Lee(2019) measured the same subject twice on different days, so the session was divided and confirmed. For direction instruction to subjects, arrows were used in Shin(2016) and Lee(2019) while text was used in Cho(2017). In Shin(2016), the subjects started imagery at the appearance of the fixation cross that is 2 sec. after the delivery of the instruction cue. For ERP analysis, we conducted preprocessing as a common average reference, filtering (0.5 to 10 Hz), baseline correction, and epoching at -2 to 2 sec. based on MI onset.

Figure 1 represents the grand average of ERPs over all subjects on the C4 channel for each dataset. At the time when the instruction cue appeared, it can be seen that the amplitude of the left MI was higher than that of the right MI in the C4 (Shin(2016): 1.75/0.43 (left/right), Lee$_{s2}$(2019): 1.02/0.53, Cho: 1.76/0.65), and the opposite patterns were found in the C3 (Shine: 0.98/1.32, Lee$_{s2}$: 0.79/1.02, Cho: 1.47/1.71). In addition, the ERP peaks look faster and steeper in arrow stimuli (Shin(2016) and Lee(2019)) than in letter stimuli (Cho(2017)).

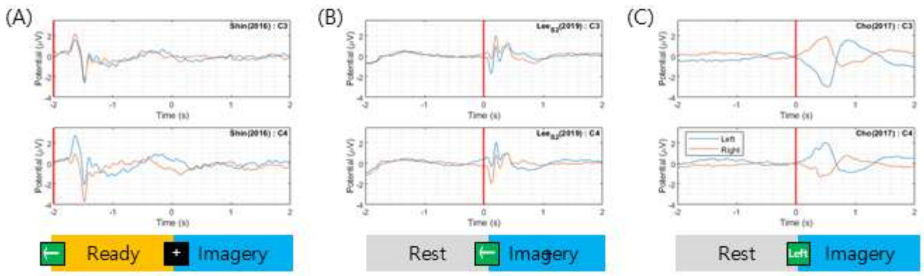

Figure 1. *Event-related potentials of motor imagery on C4 (Lee(2019) and Cho(2017)) or FCC4h (Shine(2016)) electrode. The red line shows the instruction cue, and the 0 of x-axis represents the motor imagery onset.*

Discussion: We found the contralateral strong ERP in the three MI datasets. Interestingly, such ERP presents after the instruction cue, not after MI onset (0 sec.) in Shin(2016). From this, we can infer that the ERPs may be less associated with imagination but may reflect cognitive processing. Indeed, we also observed the different temporal patterns of ERP between arrow and text. Additional work on more data and new experiments may help in drawing solid conclusions.

Significance: In previous MI studies, there was no consideration of the low frequency band (ERP), but in the MI paradigm, there are differences depending on the direction.

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Joie: An Affective Brain-computer Interface (BCI) for Learning Mental Strategies for Positive Affect

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Introduction: Neurofeedback training to increase left frontal brain activity may help reduce symptoms of anxiety and depression [1]. We designed Joie, a novel affective brain-computer interface (BCI) which seeks to help users learn mental strategies for positive affect that can be used to regulate frontal alpha asymmetries. We evaluated the impact of teaching users mental strategies on BCI performance, defined as the increase in left-frontal activity after 5 training sessions.

Material, methods and results: We recruited participants (N=20, M= 11, F= 8, NB=1, Age_{mean} = 27.65, Age_{range}= [21,44]) who reported having no known gastrointestinal, neurological, or psychiatric disorders except for anxiety conditions, to play 5 Joie sessions over two weeks (40 minute gameplay, 3x 8-minute training per session). Participants in our experimental group were taught about approach and withdrawal motivation [2] and instructed to “imagine people or animals they love”, “positive upbeat music”, “future or past happy memories”, or create their own similar strategy. We found that number of training sessions significantly predicted increased baseline-adjusted left-activation for our experimental group ($G_{treatment}$: $F_{2,102} = 3.31$, $P < .05^*$, $R^2 = 0.06$) while for the placebo and control groups no significant change was observed ($G_{placebo}$: $F_{2,90} = 0.881$, $P > .05$, $R^2 = -0.002$, $G_{control}$: $F_{2,83} = 1.86$, $P > .05$, $R^2 = 0.02$).

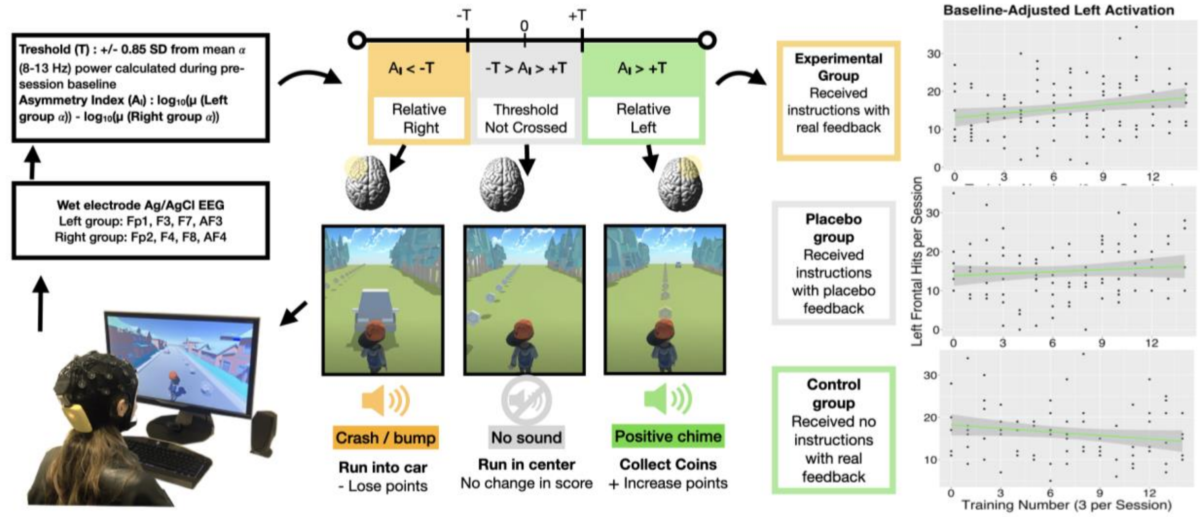

Figure 1. The Joie gameplay setup, operant conditioning paradigm and experimental results. When participants would cross the “relative left” threshold, their character would collect coins. Only the experimental group saw a group-level positive increase.

Discussion and Significance: The participants in the experimental group learned to regulate their frontal alpha over training sessions. The results support the use of the approach and withdrawal model of emotion to create BCIs, also seen in [3]. They also support the possibility that with minimal instruction and guidance, users can learn to create cognitive strategies to modulate frontal asymmetries. Future research directions can expand on this result to demonstrate how this can be used to reduce anxious or depressive symptoms.

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Adaptive task designer for optimized training of a motor ECoG-based Brain-Computer Interface: toward unassisted closed loop BCI training.

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Introduction: Motor Brain-Computer Interfaces (BCI) are now showing impressive performances in the laboratory. However, there are still some challenges to be addressed before functional neuroprostheses can be used for daily-life applications. Online closed loop decoder adaptation (CLDA) is known to be efficient procedure for BCI decoders training, allowing to take into account the day-to-day variability of the brain signals as well as the neuronal feedback, when controlling an effector. These calibration procedures are often based on supervised learning techniques, thus require a clinician to cue the patient with target movements. For a home-use application, decoder calibration is required to be unassisted by trained staff. In this context, we developed an automated task designer, which supervises the calibration phases by giving target movements that are both optimal for the decoding model training and for the patient commitment. In a daily-life application of BCI neuroprostheses, task designers would allow to have model evolving, able to cope with day-to-day variability and patient improvement.

Materials, methods and Results: The automatic task designer consists in multiple parts. First, a performance measurement system has been specifically designed to assess the efficiency of the different parts of our decoding model for each task [1,2]. The convergence of each part of the model and across the multiple calibration steps is also evaluated. Additionally, patient related criteria have been added to take into account task repetitions and exploration to improve the patient commitment in the training process. Finally, multiple strategies merge these criteria to define in an online manner the sequence of tasks proposed to the patient.

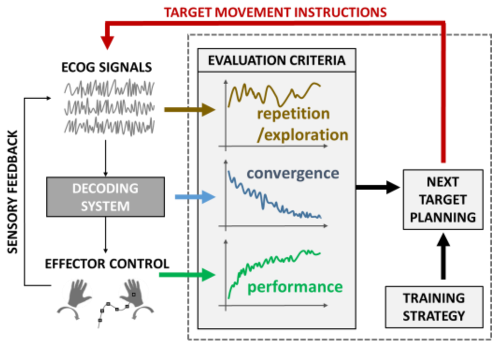

Figure 1. Schematic of the task designer principle

The different strategies for task designer have been tested on pre-recorded data from the "BCI and Tetraplegia" clinical trial (NCT02550522, ClinicalTrials.gov). The data recorded come from 8-dimensional alternative control of both arms (3D translation and 1D rotation of each hand). The dataset has been segmented in trials, corresponding each time a new target movement has been asked to the patient. New decoding models have been calibrated as it would have been trained in online experiments by picking trials through the different training strategies. These models have been evaluated by testing on a fixed test dataset. The strategies tested so far are limited to random picking (as a baseline comparison), worst performance movement first, and combined ranking according to all criteria.

Discussion and perspectives: Other strategies combining performance, convergence and patient related criteria should be tested. Tuning of the decision hyperparameters as well as testing of the most promising strategies in online experiment are to be carried out.

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