Case studies on visual ERP-based brain-computer interface use by individuals with severe speech, physical, speech and eye movement impairments

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Abstract

Individuals with severe speech and physical impairment face significant challenges in communication and daily interaction. Visual brain-computer interfaces (BCIs) offer a potential assistive solution, but their usability is limited when facing eye motor impairments that affect gaze fixation and visuospatial attention (VSA). This study investigates the feasibility of a gaze-independent visual oddball BCI for individuals with severe speech, physical and gaze impairment (SSPGI). Seven participants with varying degrees of eye motor impairments were recruited and BCI decoding accuracy evaluated under three conditions: overt, covert, and free VSA using multiple classification methods. Results confirm that covert VSA with central fixation leads to decreased accuracy, whereas uncued VSA is comparable to overt VSA in some gaze-impaired participants. Furthermore, cross-condition decoder training and evaluation suggests that training with overt VSA may improve performance in gaze-impaired individuals. These findings highlight the need for adaptive decoding strategies and further validation in applied settings used by impaired individuals.

1 Introduction

Neurological conditions, such as acquired brain lesions, neuromuscular disorders and Amyotrophic Lateral Sclerosis (ALS) can result in severe speech and physical impairment. This, in turn, significantly alters an individual's ability to communicate and interact with their environment, reducing the level of activity and participation, and overall quality of life. Assistive and augmentative communication (AAC) technology [3, 8, 7] leveraging visual brain-computer interfaces (BCIs)[32, 26], which relies on the interpretation of visual stimuli by the user, offers several advantages in this context. The rapid stimulation pace of visual BCIs and the modulation of information over spatial attention allow for high information transfer rates (ITRs) [1, 13]. Combined with their ability to operate with non-invasive recording technology, this makes them well-suited for real-time communication tasks.

However, severe visual impairments such as nystagmus (uncontrolled eye movements), diplopia (double vision), ophthalmoplegia (eye paralysis) fatigability and head motion limitations can significantly hinder the ability to use visual BCIs. These impairments make it difficult for BCI users to track or focus on visual stimuli accurately, reducing their performance with BCIs that rely on visual cues [21, 11, 25]. Unfortunately, it is again for this group that eye tracking solutions also perform poorly, making them more reliant on potential developments in BCIs that do not rely on eye gaze.

Eye motor impairments are presumed to reduce performance in operating visual BCIs [36], since users cannot comfortably redirect their gaze at the desired target, i.e., perform overt visuospatial attention (VSA). This is usually circumvented by designing gaze-independent BCIs [29]. These interfaces either avoid visual stimulation or exploit some form of covert VSA, where gaze and VSA do not coincide.

Several studies on visual oddball BCIs indicate that performance declines without fixation on the intended target [5, 35, 30], necessitating gaze-independent solutions. These studies build on the assumption that BCI users with eye motor impairment would feel comfortable operating an interface in pure covert VSA with central fixation. One could argue that a BCI verified to work only with central fixation could also be considered gaze-dependent. This does not account for the residual eye motor capabilities of most individuals with severe speech, physical and gaze impairment (SSPGI), the (dis)comfort they experience while performing gaze fixation and other confounding factors resulting from their eye motility.

It is notable that studies reporting on gaze-independent visual BCI use by individuals with SSPGI are very few. Results are usually different from those obtained with healthy control participants, due to difference in capabilities, brain response, equipment and environment.

Lesenfants et al. [19] tested a BCI using gaze-independent steady-state visually evoked potentials (SSVEPs) in six participants with Locked-in Syndrome (LiS) yet they only exceeded chance level accuracy in two. More recently, Peters et al. [27] performed a trial with two participants with late-stage ALS with severe visual impairment. Their SSVEP paradigm was not optimized for gaze-independence, but the system showed high accuracy, outperforming an eye tracking alternative. It would be of interest to determine whether such results can be replicated with participants with other neurological conditions, and with a visual oddball rather than an SSVEP paradigm.

Orhan et al. [23] and Oken et al. [22] tested the rapid serial visual presentation (RSVP) speller with individuals with LiS. Due to the serial nature of the stimulation paradigm, communication was rather slow but they demonstrated viability of the RSVP paradigm in a relevant target population.

Severens et al. [33] evaluated the visual Hex-o-Spell [35] on 5 participants with ALS and showed that this visual oddball interface optimized for gaze-independence can outperform a tactile BCI. While this speaks to the power of visual paradigms even in groups that are expected to have eye motor impairment, they did not verify the gaze direction of participants during the experiment. It was assumed that participants were performing overtly. Participants with ALS also exhibited a substantially lower accuracy than healthy controls (58% vs. 88%).

Van Den Kerchove et al. [37] also built towards a gaze-independent solution using the visual Hex-o-Spell interface [37]. They partially accounted for the fact that BCI users with SSPGI might not fully rely on central gaze fixation by evaluating settings independent of central fixation. They showed gaze-independent performance can be improved in healthy subjects by using a suited decoding strategy that corrects for latency jitter in covert VSA responses. Yet, there is a need for verification of these results in individuals with SSPGI.

Ultimately, this research aims to develop gaze-independent BCI for individuals who are fully locked-in and have no alternative means of communication. However, this group is very small and it is often challenging to recruit them into a study and perform experiments [38]. Individuals with less severe paralysis or in less progressed disease stages that struggle with eye-tracking technology could also benefit from solutions tailored to their specific situation and remaining capabilities. Therefore, we apply the concepts from earlier work and literature to individuals with severe speech and physical impairment affected by various degrees of eye motor impairment using a visual oddball BCI. The contributions of this study are as follows: (1) recruit individuals that are specifically affected with SSPGI in a visual BCI study. (2) explore their capabilities and experienced comfort when operating such a BCI, (3) evaluate the performance of a gaze-independent visual BCI for this group, (4) verify if this performance can be improved with a suitable decoding strategy. Finally, we formulate a set of recommendations based on our experience with carrying out this study that could be leveraged for the design of further similar studies or BCI-AAC solutions for this target population.

2 Materials & methods

2.1 Recruitment

Participants were recruited from the Neuromuscular Reference center at University Hospital Leuven (Leuven, Belgium), TRAINM Neuro Rehab Clinics (Antwerp, Belgium), the Neurorehabilitation Unit at the Lille University Medical Center (Lille, France), and Fondation Partage et Vie (Loos, France). Ethical approval for this multi-center study was obtained from the Ethics Commission of the University Hospital Leuven (S62547). Experiments were performed under the supervision of the treating physician.

In order to be recruited, participants must:

1. be at least 18 years old and no older than 60 years,
2. belong to class 2 or 3 according to the BCI user selection criteria presented by Wolpaw et al. [38],
3. have limitations to the extent or comfort of their eye motor control (partial or full gaze paralysis, uncontrolled gaze movements, or conditions affecting the capability to direct the gaze or fixate.)
4. have given their informed consent prior to participation.

Participants were excluded if they:

1. had a diagnosis of a major medical condition, including any major neurological or psychiatric disorder other than those of interest based on inclusion criteria 2, and 3
2. had a predisposition to or a history of any kind of epileptic seizures, including photosensitive epilepsy,
3. had a severe loss in vision or hearing that would significantly impair participation in the experiment,
4. were using specific psychoactive medications or substances that could affect the outcome. (neuroleptics or benzodiazepines)
5. were unable to understand the experiment instructions and cooperate,
6. had any other limitations preventing them from performing the given task.

In total, 11 individuals were contacted. Of these, one person with Multiple Sclerosis (MS) was excluded based on criterion 3. One person recovering from traumatic brain injury (TBI) was excluded based on both 2 and 4, and one person recovering from stroke based on 1. One further person recovering from a stroke was excluded due to technical difficulties during the experimental session.

Ultimately, 7 participants were retained. Of these, one participant was diagnosed with bulbar-onset ALS, three with Friedreich's Ataxia (FRDA) an three were recovering from LiS due to stroke. Table 1 lists the included participants and their diagnoses.

2.2 Visual skills and eye motor examination

Self-reported eye motor and visual abnormalities as reported in table 2 were recorded. Visual skills were assessed using the framework established by Fried-Oken et al. [11]. These describe on a higher level the factors that can reduce visual BCI performance when impaired, and include visual acuity, visual fixation, eyelid function, ocular motility, binocular vision, and field of vision. Additionally, participants and their caregivers were asked about eye tremors (nystagmus or other) and other involuntary eye movements. Vision was assessed using a logMAR chart [4].

All participants reported some degree of fatigue or discomfort when fixating. Participant PA1 had the mildest impairment, only reporting fatigue when fixating for prolonged times. The FRDA participants were mostly affected by eye tremors and impaired

ID	Diagnosis	Age	Sex	Hand.	Speech	Trach.	Communication	W	KB
PA1	bulbar-onset ALS	58	M	L	anarthric	no	tablet	3	4
PB1	FRDA	41	M	L	dysarthric	no	verbal	3	3
PB2	FRDA	43	F	R	dysarthric	no	verbal	3	3
PB4	FRDA	48	M	R	dysarthric	no	verbal	3	3
PC2	ischemic brainstem stroke	43	M	R	anarthric	yes	eye movement	2	4
PC3	haemorrhagic brainstem stroke	43	F	R	anarthric	yes	letterboard	2	3
PC4	ischemic brainstem stroke	54	M	R	anarthric	yes	letterboard	2	3

Table 1: Included participants with their diagnosis and relevant communication capabilities. Trach.: underwent a tracheostomy, W: classification according to Wolpaw et al. [38], KB: classification according to Kübler and Birbaumer [17].

	PA1	PB1	PB2	PB4	PC2	PC3	PC4
Visual fixation	−	−	−	−	−	−	−
Eyelid function	+	+	+	+	+	−	−
Ocular motility	+	−	+	−	/	/	−
Binocular vision	+	+	+	+	−	/	/
Field of vision	+	+	+	+	+	−	−
Involuntary movement	+	−	/	−	−	−	+
Visual acuity	0.0	0.0	0.6	0.2	0.0	0.7	0.6

Table 2: Self-reported visual skills as defined by Fried-Oken et al. [11] of gaze-impaired participants included in this study. + skilled, − impaired, / severely impaired. Visual acuity was assessed using the logMAR scale (lower is better).

pursuit. PB2 suffered from especially severe horizontal oscillating involuntary eye movements. Eye motor function of participants PC2, PC3, and PC4 was most severely affected. Participant PC2 was only able to look up and down and had a deviation in the left eye causing diplopia, but this was corrected by a prism glass. Participant PC3 only retained partial motility of the right eye, while the left eye was permanently closed. Participant PC4 had one deviated eye with a corneal abscess affecting the motility and vision in the right eye, and reducing motility in the left.

Finally, we also recorded gaze position throughout the experimental session to register the participant's gaze relative to the stimulated BCI targets, using a Tobii X2-30 Compact (Tobii Technology AB, Sweden) portable eye tracker placed at the bottom of the laptop screen. The registered data was cleaned by fusing left and right eye screen-based gaze coordinates into one channel for the horizontal and one for vertical gaze position. If both were present for a given sample, the fused channel was the mean of both values. If at a given sample either the left or the right eye was not detected for a given channel, the value of the other one was adopted. If both were missing, the gaze position remained unset at that time point, and no interpolation was performed.

2.3 BCI stimulation

The BCI stimulation procedure was based on the Hex-o-Spell [35] implementation presented by Van Den Kerchove et al. [37]. Similar to this study, the task consists of counting the flashes of a cued target among 6 circular, flashing targets laid out in a hexagonal pattern in the field of view of the user as displayed in fig. 1. We refer to Van Den Kerchove et al. [37] for further details on the implementation of the stimulation procedure.

Three different VSA settings were explored. In the overt VSA setting, the participant was instructed to fixate on the cued target or to try this to the maximum extent of their visual skill, even if experiencing slight discomfort. In the covert VSA setting, the participant was instructed to fixate on the center of the screen, to the extent of their ability. An additional *free VSA* setting was introduced. Here, the participant was instructed to perform the task as they deemed most comfortable. This allowed us to investigate the user's natural way of operating the BCI given their individual set of visual skills. If the participant was not fully paralyzed, they were instructed not to move their head. The cued *split attention* setting proposed by Van Den Kerchove et al. [37] was not studied here, as we were interested in natural VSA operation settings for gaze-impaired individuals.

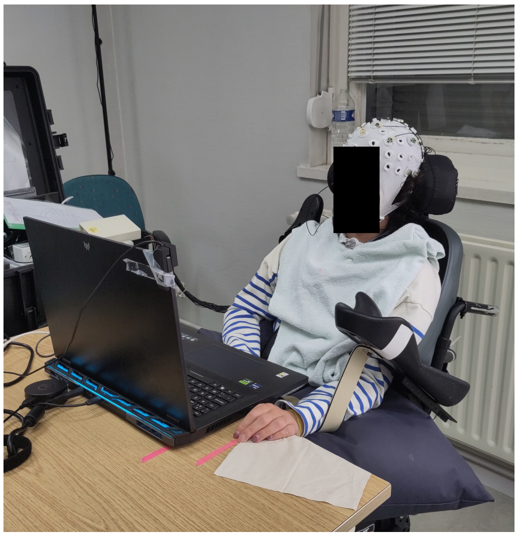
To make the interface suitable for use by individuals with participants with neurological conditions [11], the amount of blocks was reduced to 6 per VSA setting. In order to decrease task difficulty, inter-stimulus interval (ISI) was increased to 200 with added random jitter uniformly distributed between -50 ms and 50 ms. The experiment also started with a training block in each condition, where the participant was instructed with oral feedback on their counting accuracy to ensure they understood and were able to perform the task.

2.4 Electroencephalography (EEG) data collection & preprocessing

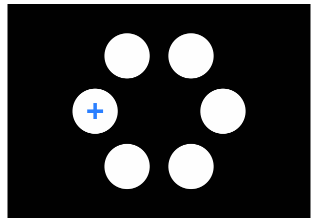
During the recording session, participants were positioned in their wheelchair in front of a table. Stimuli were presented on an Acer Predator Helios laptop with an 18" screen (Acer, Inc., Taiwan) placed at a 60 cm distance. A Cedrus StimTracker (Cedrus Corp., CA, USA) ensured synchronization of stimuli with the recorded EEG.

EEG was recorded at 1000 Hz using the Neuroscan Neuvo portable amplifier (Compumedics Neuroscan, Australia) connected to a second laptop for registration. The EEG headset used 18 active AgCl electrodes (EASYCAP GmbH, Germany) placed on a cap according to the international 10-20 layout. Using electrolyte gel, electrode impedances were reduced below 10 kΩ. Additionally, the electrooculogram (EOG) was recorded.

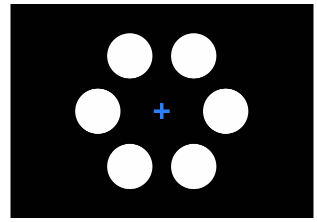
The EEG was band-pass filtered between 0.5 and 16 Hz. Bad channels were rejected using the RANSAC algorithm [9] and visual inspection. Next, the EEG was re-referenced to the average of mastoid electrodes TP9 and TP10, and independent compo-



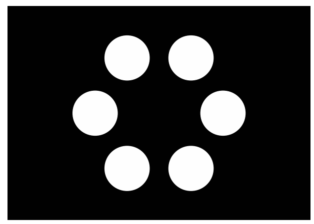
(a) A participant seated in a wheelchair in front of the stimulation laptop with EEG cap.



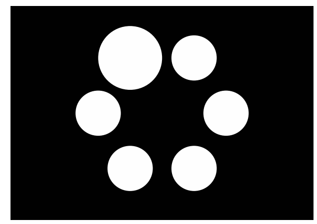
(b) Stimulation interface with 6 targets and fixation crosshair positioned for *overt* VSA.



(c) In *covert* VSA, the fixation crosshair is placed in the center of the screen.



(d) In *free* VSA, no fixation crosshair is displayed.



(e) Targets are intensified by enlarging them for 100 ms.

Figure 1: Stimulation and recording setup for the oddball BCI experiment with different VSA conditions

nent analysis (ICA) was performed to reject artifactual components based on correlation with the EOG or by visual inspection. Epochs were cut from -0.1 to 0.9 s relative to stimulus onset, and no baseline correction was performed.

2.5 BCI decoding

We evaluated the recorded EEG data using the Classifier-based Latency Estimation with Woody iterations (WCBLE) [37] and block-Toeplitz linear discriminant analysis (tLDA) [34] classifiers, as well as the Riemannian approach XDAWN-Cov+TS+LDA [6]. For WCBLE, a region of interest from 0 ms to 800 ms relative to stimulus onset was used while the epoch was cropped to -100 ms to 900 ms. For the other decoders, the epoch was cropped between 0 ms and 800 ms, which resulted in maximal accuracy. Decoding scores were obtained using 6-fold cross-validation where folds corresponded to stimulation blocks.

3 Results

3.1 Eye tracking analysis

Given their eye motor impairment as listed in table 2, we aimed to clarify the capabilities of the participants in performing overt VSA and central gaze fixation and to assess the relevance of these settings when gaze is not cued. Figure 2 maps gaze position relative to the targets across conditions. These results should be interpreted with care, as the eye tracker partially relies on intact eye motility. The participant's position relative to the eye tracker might have shifted throughout the experimental session despite our best efforts, due to e.g. a regular need for aspiration of the tracheostoma of some participants

smoothing

link to high resolution

PA1 had relatively intact gaze control and was able to correctly perform the cued overt and covert settings. When gaze was uncued, he fixated on the cued target. This was also mostly the case for PB1, although eye tracking revealed that he chose not to

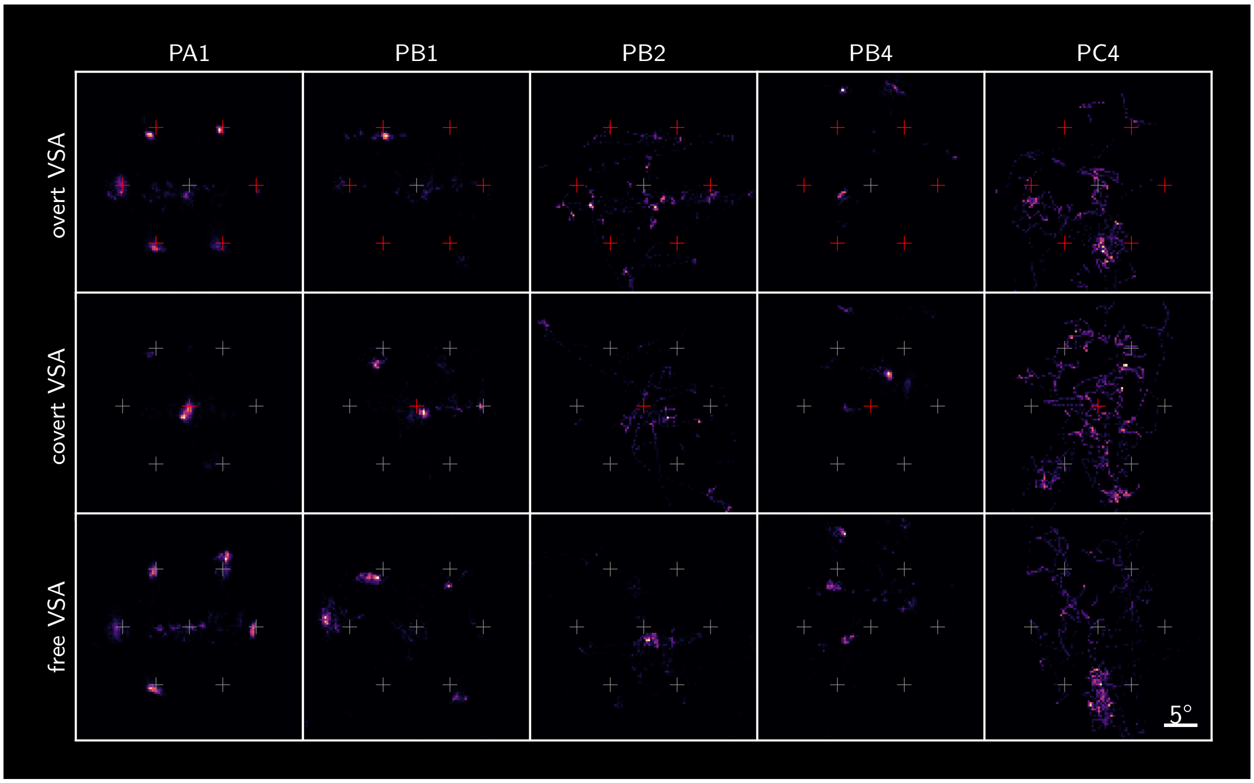


Figure 2: Distribution of the recorded gaze position during the experimental session in the three VSA conditions. Crosshairs represent stimulus positions, with positions cued during the given condition indicated in red. Subjects PB2 and PC4 preferred covert BCI operation, with PB2 resting gaze near the middle of the screen, and PC4 near the bottom.

perform central gaze fixation when cued in at least one of the stimulation blocks. We were unable to record his gaze near the bottom-left stimulus position, either due to eye tracker failure or because the participant was not comfortable fixating on this position. Eye tracker calibration did not succeed for subject PB4, but given the transformation of gaze positions to the stimulus space, they were assumed to be overtly performing the free task.

PB2 was able to perform overt VSA and central fixation to some extent, yet eye tracking shows a larger spread in gaze position compared to PA1 and PB1. In the free VSA condition, however, she preferred to attend stimuli covertly when the gaze was uncued. This was confirmed by the participant.

The overt and central gaze fixation settings were also not properly adapted to participant PC4. In the free VSA condition, eye tracker results show that his gaze was usually near the bottom two targets, indicating some degree of covert or split VSA.

Technical difficulties were encountered while recording gaze position with the Tobii X2-30 Compact for participants PC2 and PC3, since they both had one eye that was occluded respectively by the prism glass and the eyelid. Both participants reported they could not fixate on some of the stimuli.

3.2 BCI decoding performance

Figure 3 shows cross-validated single-trial target selection accuracy for the evaluated VSA settings for the different decoders. Accuracy results do not reveal a clear trend in decoder performance per condition. In the covert VSA setting with cued central gaze fixation, accuracy deteriorated overall. Target selection accuracy this task was around chance level ($\frac{1}{6}$) for participants PB4, PC2 and PC3.

WCBLE did not improve over the accuracy of tLDA in the free VSA setting, but XDAWN-Cov+TS+LDA accuracy was slightly lower here, though not significantly. More interestingly, we noticed that accuracies of the decoders in free VSA were close to those in the overt VSA. A substantial decrease in accuraciy from the overt setting to the free setting was observed for subjects PC2, PC3 and PC4 who had the most severe eye motor impairment. For PB2, who relied on covert VSA during the uncued free VSA according to gaze tracking setting, the decrease in accuracywas also present.

3.3 Cross-condition decoder training and evaluation

As an alternative approach to selecting the most suitable decoder, we used tLDA as the base decoder and verified whether accuracy could be improved if BCI users with gaze impairment performed the decoder training session session relying maximally on their residual gaze control.

Figure 4 shows that for participants PB1 and PC2 covert VSA decoding improved when training with overt VSA. Note that, according to eye tracking data, participant PB1, PB4, and PC4 did not always perform cued central gaze fixation in the covert VSA setting, which might have affected the results.

4 Discussion

This study investigated the feasibility of a gaze-independent visual oddball BCIs for individuals with SSPGI. While covert VSA with cued, central gaze fixation resulted in reduced decoding accuracy, likely due to increased task load, accuracy in free VSA where gaze position is uncued can yield performance comparable to explicitly cued overt VSA for some participants. This suggests that the evaluated participants naturally integrate residual gaze control. Training with cued, overt VSA can improve accuracy in subsequent free VSA conditions, highlighting the potential benefits of leveraging this residual eye motor control during the decoder training phase. While gaze-independent BCIs show promise for individuals with SSPGI, usability and comfort remain critical considerations for real-world applications. These results provide important insights into the optimization of visual BCIs for individuals with severe motor impairments and underscore the need for further research into adaptive decoding strategies and user-centered design.

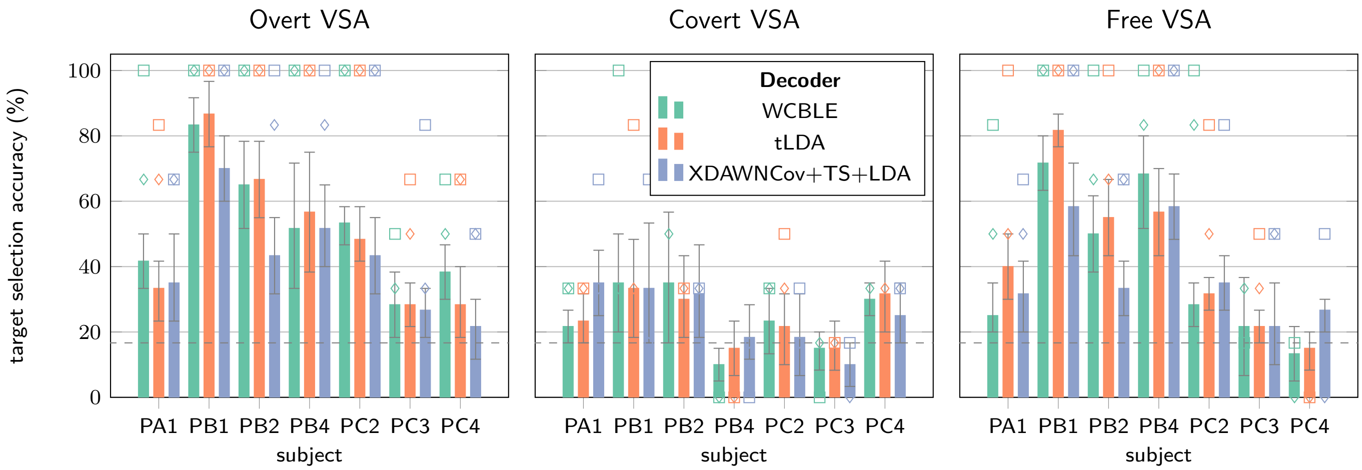


Figure 3: Decoding performance in different VSA settings reported as single-trial target selection accuracy (%). Accuracy in free VSA is generally on par with the overt VSA setting. In the covert VSA setting with central gaze fixation, accuracy is lower, but can be improved with the WCBLE decoder. Whiskers indicate 95% confidence intervals determined using 10,000 bootstrapping repetitions. Dashed line indicates the chance level accuracy. Diamond markers indicate target selection accuracy using the median score for five stimulation repetitions. Square markers indicate target selection accuracy for 10 stimulation repetitions. ($\frac{1}{6}$).

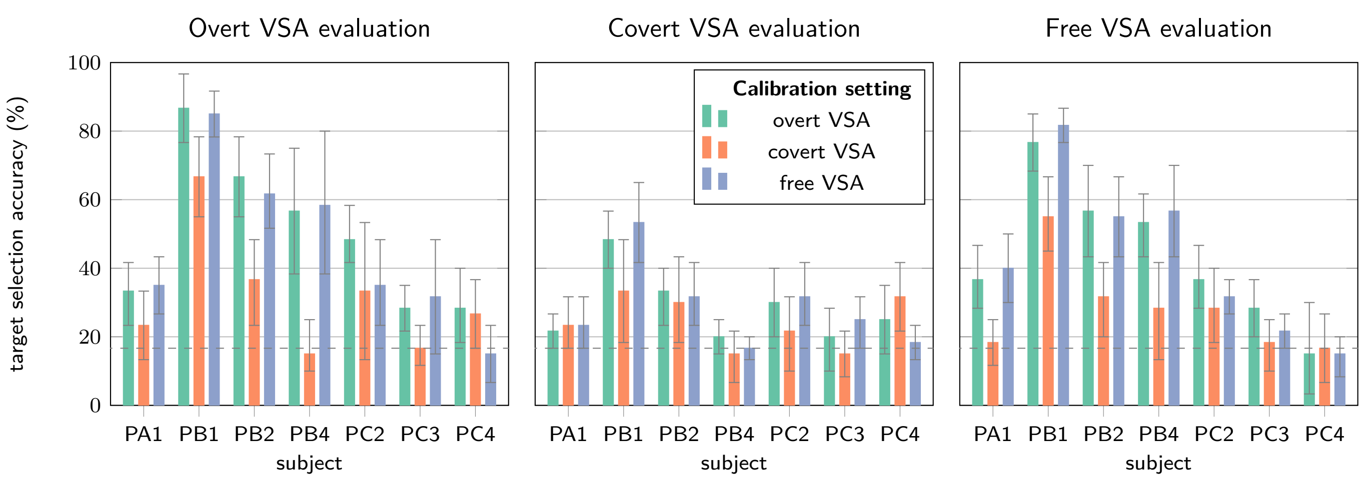


Figure 4: Decoding performance when calibrating the tLDA decoder in a given VSA setting, and evaluating it in another, reported as single-trial area under the receiver-operator characteristic curve. Whiskers indicate 95% confidence intervals determined using 10,000 bootstrapping repetitions. For participants PA1, PB2, and PC3, decoding accuracy in the covert VSA setting with central gaze fixation improved when calibrating with overt gaze fixation.

4.1 Gaze-independent operation & decoding

Due to the heterogeneous nature of the participants' conditions and the limited number of participants, it is difficult to draw general conclusions. This study should therefore be seen as a collection of case studies, highlighting different obstacles encountered in developing gaze-independent visual oddball BCIs for individuals with SSPGI. Nevertheless, we highlight some aspects that might be of interest for the further development of this class of BCIs.

True *gaze-independent* visual BCIs should not rely on gaze fixation. Hence, our analysis centers around the free VSA condition. Eye tracking results presented in section 3.1 confirm our assumption that voluntary covert VSA can occur in individuals with SSPGI. We also confirmed part of the results presented by Van Den Kerchove et al. [37], which state that decoding of covert VSA with central gaze fixation can be improved by accounting for latency jitter. We showed that this also holds for some individuals with SSPGI, with PA1 and PC4 as examples.

Contrary to our assumptions, we have shown that accounting for latency jitter does not necessarily improve covert VSA when gaze fixation is not cued. One possible explanation is that actively performing central gaze fixation increases task load. This, in turn, can reduce overall performance, even though the participant might have otherwise performed covert VSA, but would not be occupied with maintaining strict central gaze fixation. This extra task demand is not present in the free VSA condition, so there is less performance to be gained. Furthermore, cued central gaze fixation combined with counting flashing stimuli in the visual periphery is an explicit example of a dual task. Dual tasks have been shown to increase P3 latency jitter [28, 2, 37], which is what WCBLE accounts for. Hence, increased P3 jitter might be more related to maintaining central gaze fixation than to the actual covert VSA aspect.

The seemingly stable accuracy across overt and free VSA could be misinterpreted as an indication that the Hex-o-Spell BCI already works well for individuals with SSPGI, and no optimization is needed. However, we assume that overt VSA accuracy was also decreased in some subjects or for some blocks if the participant was not able to comfortably perform the task. Nevertheless, the large difference between the free VSA setting and the covert VSA setting with central gaze fixation is food for thought about the applicability of solutions developed with central fixation in mind.

Individuals with all except the most severe gaze impairments will likely retain some capability to direct their gaze in visual BCI operation, which can drastically boost accuracy. Subject PB2 exemplifies this: his free VSA decoding accuracy is above that in covert VSA, and eye tracking showed that he relied mostly on overt VSA when cued to do so, and mostly on covert VSA when gaze was uncued. This is also supported by our results on cross-condition decoder training and evaluation presented in section 3.3, which show that leveraging residual eye motor control to fixate targets during the decoder training phase can improve decoding accuracy in some settings. This is likely due to the increased P3 component amplitude in overt VSA, which improves the discriminative power of a classifier trained on this data. Cueing this overt gaze fixation only during the decoder training phase leaves the user free to operate in the manner that is most comfortable in the operation phase. Early VEPs in the training data could also contribute in those cases where the participant was not able to perform covert VSA with central gaze fixation.

4.2 Clinical implications

The population of individuals with SSPGI is sparse, yet is regularly confronted with major challenges. As opposed to individuals in a vegetative or severe minimally conscious state, they demonstrably have the intent and capability to communicate their thoughts and desires to their clinicians, caregivers and social network. These capabilities, however, are severely limited by their condition, reducing the effectiveness and efficiency of communication. Hence, finding a way to fill in this gap is a major issue in the care of individuals with SSPGI.

Our work shows that some patients might benefit from visual BCIs for home use or in the clinical setting. While the proposed communication protocol is a proof of concept with a limited degree of freedom, it is a step towards applications like textual communication and environment or home automation control that inherits the relatively high information transfer rate of visual BCIs.

Furthermore, our experiments revealed that the required technology and its potential applications were generally well received by the participants and their environment. While the necessary visual attention task can be taxing if performed for extended periods of time, participants indicated that this was outweighed by the potential to communicate in a more automated and autonomous way compared to their current AAC solutions, which often required the help of a trained caregiver.

4.3 Limitations & recommendations

Despite the insights gained on gaze-independent BCI approaches, certain limitations must be addressed in future research. First and foremost, this study works with a limited sample size, which does not represent the full spectrum of individuals with SSPGI and their specific symptoms and skills. Individuals with FRDA met the inclusion criteria, but they are usually not considered one of the typical interest groups for BCI communication assistive technology, partly due to the rarity of the disease and partly due to its progression. It would be most interesting to verify these results with individuals with LiS and no eye movement capability at all.

Another limiting factor is the difficulty experienced in correctly interpreting eye tracker results in studies with individuals with gaze impairments. If eye tracking is possible at all, it is not guaranteed that the user is able to successfully perform the calibration procedure. Further experiments should be carried out with a stationary eye tracker with more advanced capabilities, although systems using a head fixator or headrest should be avoided. This is not practical when working with wheelchair-bound individuals who might have undergone a tracheostomy and may suffer from spasticity. Given different more suited gaze tracking hardware, adapted to the participant's conditions, analyses could be performed with a finer granularity by assessing the gaze condition on a per-epoch basis.

To properly contextualize performance results, they should be coupled with metrics evaluating the full scope of the user's requirements, with measures of usability, comfort and perceived effort, like the NASA Task Load Index [15]. Decoding accuracy might, after all, be traded off for user comfort. The perception of this type of BCI by the user might also be influenced by performing the experiment in an online manner, providing immediate feedback after selection and thus closing the loop. In this study, user comfort in the different conditions was not objectively measured. Instead, it was assumed that participants operated most comfortably in the free VSA condition. Even though participants reported that they could comfortably operate the system, this must be confirmed with more quantitative assessments.

if no eye motor report: Eye motor disability could also have been assessed more objectively [11], using, e.g., the Revised Coma Recovery Scale [12] or the NSUCO oculomotor exam [20].

To optimize BCI user experience, research must extend beyond offline classification performance and address the full scope of user interaction during online use. Offline evaluation, while convenient, fails to capture critical factors such as user engagement, learning effects, and true satisfaction. A user-centered design (UCD) framework offers a structured approach to evaluate effectiveness, efficiency, and satisfaction in realistic settings [16, 31, 18, 14]. This includes transitioning from abstract stimuli to meaningful interfaces providing immediate feedback, and evaluating performance metrics in real-time. Satisfaction, a subjective yet vital component, should be assessed through questionnaires after realistic online use [18]. Decoder development, interface design, and paradigm selection should be co-optimized, as improvements in decoding alone may be insufficient if the paradigm does not align with the user's abilities and preferences. Ultimately, the goal is to design a usable system for individuals with specific impairments, where longitudinal studies with targeted user groups or individuals are required to evaluate system performance comprehensively.

Implementing such a user-centered approach requires early and active involvement of individuals with SSPI throughout the research process [16]. Instead of a traditional bottom-up approach – starting with healthy controls and offline analysis – similar future projects should begin directly with online experiments in the target population, identifying challenges and iteratively optimizing the system [11]. This requires long-term collaboration with patient centers to ensure an involved team of clinicians, occupational and speech therapists, and other caregivers, next to further arrangements like ethical approval, and access to suitable infrastructure from the onset. Maintaining a functional in-house online BCI-AAC system facilitates iterative development and realistic performance estimation, ensuring experimental settings reflect practical use. While this top-down approach may not suit novel BCI paradigms in early development, it is appropriate for mature paradigms such as visual oddball BCIs [24, 10], where the main challenge lies in usability and disseminating the technology to potential users.

5 Conclusion

This study explored the usability of electroencephalography (EEG)-based gaze-independent visual BCIs in individuals with severe speech, physical and gaze impairment (SSPGI), focusing on the impact of eye motor impairments on performance. Our results demonstrate that a visual brain-computer interface (BCI) gaze-independent operation is feasible for some of these individuals. They might either achieve sufficient decoding accuracy despite their eye motor impairment, or performance can be enhanced by careful, individual adaptation the decoding strategies. The free visuospatial attention (VSA) condition yielded decoding accuracy comparable to overt VSA in some participants, suggesting that users may naturally integrate residual gaze control. Additionally, training under overt VSA conditions improved accuracy in subsequent covert or free VSA operation, highlighting the potential benefits of leveraging residual eye motor capabilities during decoder training.

While these findings are promising, future work should include larger participant groups, refine stimulation paradigms, and incorporate user-centered assessments of comfort and usability to actively develop usable solutions. Ultimately, optimizing gaze-independent BCI designs could enhance communication options for individuals with severe motor and speech impairments, particularly those who struggle with conventional eye-tracking technologies.

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Appendix

References

[1] Reza Abiri et al. "A comprehensive review of EEG-based brain–computer interface paradigms". en. In: *J. Neural Eng.* 16.1 (Jan. 2019), p. 011001. ISSN: 1741-2552. DOI: 10.1088/1741-2552/aaf12e.

[2] P. Aricò et al. "Influence of P300 latency jitter on event related potential-based brain–computer interface performance". en. In: *J. Neural Eng.* 11.3 (May 2014), p. 035008. ISSN: 1741-2552. DOI: 10.1088/1741-2560/11/3/035008. (Visited on 03/23/2023).

[3] Rúbia Eliza de Oliveira Schultz Ascari, Roberto Pereira, and Luciano Silva. "Mobile interaction for augmentative and alternative communication: a systematic mapping". In: *Journal on Interactive Systems* 9.2 (Aug. 2018). ISSN: 2763-7719. DOI: 10.5753/jis.2018.704.

AAC	assistive and augmentative communication
ALS	Amyotrophic Lateral Sclerosis
BCI	brain-computer interface
EEG	electroencephalography
EOG	electrooculogram
FRDA	Friedreich's Ataxia
ICA	independent component analysis
ISI	inter-stimulus interval
ITR	information transfer rate
LiS	Locked-in Syndrome
MS	Multiple Sclerosis
RSVP	rapid serial visual presentation
SSPGI	severe speech, physical and gaze impairment
SSVEP	steady-state visually evoked potential
TBI	traumatic brain injury
tLDA	block-Toeplitz linear discriminant analysis
UCD	user-centered design
VSA	visuospatial attention
WCBLE	Classifier-based Latency Estimation with Woody iterations

Table A1: List of acronyms.

[4] Ian L Bailey and Jan E Lovie. "New design principles for visual acuity letter charts". In: *Optom. Vis. Sci.* 53.11 (Nov. 1976), pp. 740–745. ISSN: 1040-5488. DOI: 10.1097/00006324-197611000-00006.

[5] P. Brunner et al. "Does the 'P300' speller depend on eye gaze?" en. In: *J. Neural Eng.* 7.5 (Sept. 2010), p. 056013. ISSN: 1741-2552. DOI: 10.1088/1741-2560/7/5/056013. URL: https://dx.doi.org/10.1088/1741-2560/7/5/056013 (visited on 11/22/2022).

[6] Hubert Cecotti et al. "Single-trial detection of event-related fields in MEG from the presentation of happy faces: Results of the Biomag 2016 data challenge". In: *2017 39th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*. IEEE. IEEE, July 2017, pp. 4467–4470. DOI: 10.1109/embc.2017.8037848.

[7] Humphrey Curtis, Timothy Neate, and Carlota Vazquez Gonzalez. "State of the art in AAC: A systematic review and taxonomy". In: *Proceedings of the 24th International ACM SIGACCESS Conference on Computers and Accessibility*. 2022, pp. 1–22. DOI: 10.1145/3517428.3544810.

[8] Yasmin Elsahar et al. "Augmentative and alternative communication (AAC) advances: A review of configurations for individuals with a speech disability". In: *Sensors* 19.8 (2019), p. 1911. DOI: 10.3390/s19081911.

[9] Martin A. Fischler and Robert C. Bolles. "Random sample consensus: a paradigm for model fitting with applications to image analysis and automated cartography". In: *Commun. ACM* 24.6 (June 1981), pp. 381–395. ISSN: 0001-0782. DOI: 10.1145/358669.358692. URL: https://dl.acm.org/doi/10.1145/358669.358692 (visited on 07/05/2023).

[10] Islam A Fouad et al. "Improving the performance of P300 BCI system using different methods". In: *Network Modeling Analysis in Health Informatics and Bioinformatics* 9.1 (Sept. 2020), p. 64. ISSN: 2192-6670. DOI: 10.1007/s13721-020-00268-1.

[11] Melanie Fried-Oken et al. "Human visual skills for brain-computer interface use: a tutorial". In: *Disability and Rehabilitation: Assistive Technology* 15.7 (June 2020), pp. 799–809. ISSN: 1748-3115. DOI: 10.1080/17483107.2020.1754929.

[12] Joseph T Giacino, Kathleen Kalmar, and John Whyte. "The JFK Coma Recovery Scale-Revised: measurement characteristics and diagnostic utility". In: *Archives of physical medicine and rehabilitation* 85.12 (Jan. 2004), pp. 2020–2029. ISSN: 1362-301X. DOI: https://doi.org/10.1080/02699050802403557.

[13] Jin Han et al. "A high-speed hybrid brain-computer interface with more than 200 targets". In: *J. Neural Eng.* 20.1 (Jan. 2023), p. 016025. ISSN: 1741-2552. DOI: 10.1088/1741-2552/acb105.

[14] Yiyuan Han et al. "Two sides of the same coin: adaptation of BCIs to internal states with user-centered design and electrophysiological features". In: *Brain-Computer Interfaces* 9.2 (Mar. 2022), pp. 102–114. ISSN: 2326-2621. DOI: 10.1080/2326263x.2022.2041294.

[15] Sandra G Hart. "NASA-task load index (NASA-TLX); 20 years later". In: *Proceedings of the human factors and ergonomics society annual meeting*. Vol. 50. 9. Sage publications Sage CA: Los Angeles, CA. American Psychological Association (APA), 2006, pp. 904–908. DOI: 10.1037/e577632012-009.

[16] International Organization for Standardization. "Ergonomics of Human System Interaction—Part 210: Human-Centered Design for Interactive Systems (formerly known as 13407)". In: *ISO FDIS* 9241.210 (2009), p. 2009.

[17] Andrea Kübler and Niels Birbaumer. "Brain–computer interfaces and communication in paralysis: Extinction of goal directed thinking in completely paralysed patients?" In: *Clinical neurophysiology* 119.11 (Nov. 2008), pp. 2658–2666. ISSN: 1388-2457. DOI: 10.1016/j.clinph.2008.06.019.

[18] Andrea Kübler et al. "The user-centered design as novel perspective for evaluating the usability of BCI-controlled applications". In: *PloS one* 9.12 (Dec. 2014). Ed. by Stefano Federici, e112392. ISSN: 1932-6203. DOI: 10.1371/journal.pone.0112392.

[19] Damien Lesenfants et al. "An independent SSVEP-based brain–computer interface in locked-in syndrome". In: *Journal of neural engineering* 11.3 (May 2014), p. 035002. ISSN: 1741-2552. DOI: 10.1088/1741-2560/11/3/035002.

[20] WC Maples. "Northeastern State University College of Optometry'Oculomotor norms". In: *J Behav Optom* 3 (1992), pp. 143–150.

[21] Lynn M McCane et al. "Brain-computer interface (BCI) evaluation in people with amyotrophic lateral sclerosis". In: *Amyotrophic lateral sclerosis and frontotemporal degeneration* 15.3-4 (Feb. 2014), pp. 207–215. ISSN: 2167-9223. DOI: 10.3109/21678421.2013.865750.

[22] Barry S Oken et al. "Brain–computer interface with language model-electroencephalography fusion for locked-in syndrome". In: *Neurorehabilitation and neural repair* 28.4 (2014), pp. 387–394.

[23] Umut Orhan et al. "RSVP keyboard: An EEG based typing interface". In: *2012 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP)*. IEEE. IEEE, Mar. 2012, pp. 645–648. DOI: 10.1109/icassp.2012.6287966.

[24] Jiahui Pan et al. "Advances in P300 brain–computer interface spellers: toward paradigm design and performance evaluation". In: *Front. Hum. Neurosci.* 16 (Dec. 2022), p. 1077717. ISSN: 1662-5161. DOI: 10.3389/fnhum.2022.1077717.

[25] Emanuele Pasqualotto et al. "Usability and workload of access technology for people with severe motor impairment: a comparison of brain-computer interfacing and eye tracking". In: *Neurorehabilitation and neural repair* 29.10 (Mar. 2015), pp. 950–957. ISSN: 1552-6844. DOI: 10.1177/1545968315575611.

[26] Betts Peters et al. "A systematic review of research on augmentative and alternative communication brain-computer interface systems for individuals with disabilities". In: *Frontiers in human neuroscience* 16 (July 2022), p. 952380. ISSN: 1662-5161. DOI: 10.3389/fnhum.2022.952380.

[27] Betts Peters et al. "SSVEP BCI and eye tracking use by individuals with late-stage ALS and visual impairments". In: *Front. Hum. Neurosci.* 14 (Nov. 2020), p. 595890. ISSN: 1662-5161. DOI: 10.3389/fnhum.2020.595890.

[28] John Polich. "Updating P300: An integrative theory of P3a and P3b". en. In: *Clin. Neurophysiol.* 118.10 (Oct. 2007), pp. 2128–2148. ISSN: 1388-2457. DOI: 10.1016/j.clinph.2007.04.019. URL: https://www.sciencedirect.com/science/article/pii/S1388245707001897 (visited on 08/10/2023).

[29] A. Riccio et al. "Eye-gaze independent EEG-based brain–computer interfaces for communication". en. In: *J. Neural Eng.* 9.4 (July 2012), p. 045001. ISSN: 1741-2552. DOI: 10.1088/1741-2560/9/4/045001. URL: https://doi.org/10.1088/1741-2560/9/4/045001 (visited on 03/31/2022).

[30] Ricardo Ron-Angevin et al. "Impact of speller size on a visual P300 brain-computer interface (BCI) system under two conditions of constraint for eye movement". In: *Computational Intelligence and Neuroscience* 2019 (2019).

[31] Martijn Schreuder et al. "User-centered design in brain-computer interfaces – A case study". In: *Artificial intelligence in medicine* 59.2 (Oct. 2013), pp. 71–80. ISSN: 0933-3657. DOI: 10.1016/j.artmed.2013.07.005.

[32] Tanja Schultz et al. "Biosignal-based spoken communication: A survey". In: *IEEE/ACM Transactions on Audio, Speech, and Language Processing* 25.12 (2017), pp. 2257–2271. DOI: 10.1109/taslp.2017.2752365.

[33] M Severens et al. "Comparing tactile and visual gaze-independent brain–computer interfaces in patients with amyotrophic lateral sclerosis and healthy users". In: *Clinical neurophysiology* 125.11 (Nov. 2014), pp. 2297–2304. ISSN: 1388-2457. DOI: 10.1016/j.clinph.2014.03.005.

[34] Jan Sosulski and Michael Tangermann. "Introducing Block-Toeplitz Covariance Matrices to Remaster Linear Discriminant Analysis for Event-related Potential Brain-computer Interfaces". In: *arXiv:2202.02001 [cs, q-bio]* (Feb. 2022). arXiv: 2202.02001. URL: http://arxiv.org/abs/2202.02001 (visited on 03/10/2022).

[35] Matthias S Treder and Benjamin Blankertz. "(C)overt attention and visual speller design in an ERP-based brain-computer interface". In: *Behavioral and brain functions* 6.1 (2010), pp. 1–13. DOI: 10.1186/1744-9081-6-28.

[36] Arne Van Den Kerchove et al. "A visual Brain-Computer Interface for gaze-free communication". PhD thesis. KU Leuven, University of Lille, 2024.

[37] Arne Van Den Kerchove et al. "Correcting for ERP latency jitter improves gaze-independent BCI decoding". In: *J. Neural Eng.* 21.4 (July 2024), p. 046013. ISSN: 1741-2552. DOI: 10.1088/1741-2552/ad5ec0.

[38] Jonathan R Wolpaw et al. "BCI meeting 2005-workshop on signals and recording methods". In: *IEEE Transactions on neural systems and rehabilitation engineering* 14.2 (June 2006), pp. 138–141. ISSN: 1558-0210. DOI: 10.1109/tnsre.2006.875583.