

Visual ERP-based brain-computer interface use with with severe speech, physical, speech and eye movement impairments: case studies

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Abstract

Background: 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 eye motor impairment in addition to physical and speech impairment. *Methods:* Seven participants with varying degrees of eye motor impairments were recruited and BCI decoding accuracy evaluated

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under three conditions: overt, covert, and free VSA using multiple classification methods. *Results:* 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. *Conclusions:* These findings highlight the need for adaptive decoding strategies and further validation in applied settings used by impaired individuals.

Keywords: brain-computer interface, assistive and augmented communication event-related potential, covert visuospatial attention, eye motor impairment, decoding

1 Background

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 [1, 2, 3] leveraging visual brain-computer interfaces (BCIs)[4, 5], 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) [6, 7]. 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 [8, 9, 10]. 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 [11], 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 [12]. 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 [13, 14, 15], 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. [16] 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. [17] 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. [18] and Oken et al. [19] 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. [20] evaluated the visual Hex-o-Spell [14] 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. [21] also built towards a gaze-independent solution using the visual Hex-o-Spell interface [21]. 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 [22]. 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 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). 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. [22],
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)

ID	Diagnosis	Age	Sex	Speech	Communication	W	KB
PA1	bulbar-onset ALS	58	M	anarthric	tablet	3	4
PB1	FRDA	41	M	dysarthric	verbal	3	3
PB2	FRDA	43	F	dysarthric	verbal	3	3
PB4	FRDA	48	M	dysarthric	verbal	3	3
PC2	ischemic brainstem stroke	43	M	anarthric	eye movement	2	4
PC3	hemorrhagic brainstem stroke	43	F	anarthric	letterboard	2	3
PC4	ischemic brainstem stroke	54	M	anarthric	letterboard	2	3

Table 1: Included participants with their diagnosis and relevant communication capabilities. W: classification according to Wolpaw et al. [22], KB: classification according to Kübler and Birbaumer [23].

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) and three were recovering from LiS due to stroke. Table 1 lists the included participants and their diagnoses, each case is clinically described in appendix A.

2.2 Visual skill and eye motor examination

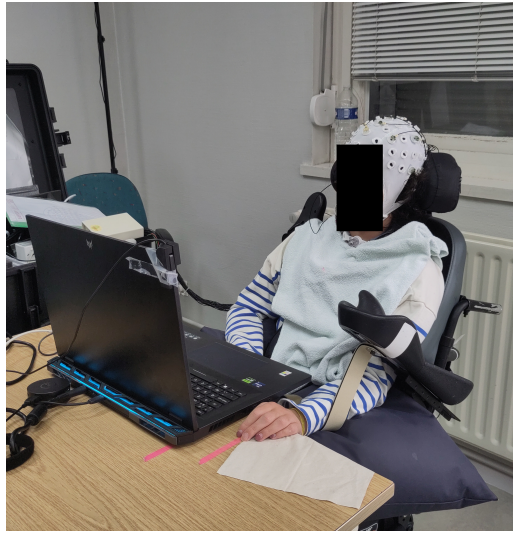
Self-reported eye motor and visual abnormalities or those observed in clinical assessment are reported in table 2. Visual skills were assessed using the framework established by Fried-Oken et al. [9]. These describe on a higher level the factors that can reduce visual BCI performance when impaired, and 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 [24].

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 pursuit. Eye motor function of participants PC2, PC3, and PC4, those recovering from brain stem and cerebellar stroke, was most severely affected.

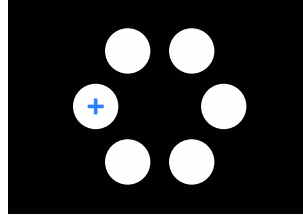
Finally, we also recorded gaze position throughout the experimental session to register the participant’s gaze relative to the stimulated BCI targets, using a Tobii X2-30 Compact (Tobii Technology AB, Sweden) portable eye tracker placed at the bottom of the laptop screen. The registered data was cleaned by fusing left and right eye screen-based gaze coordinates into one channel for the horizontal and one for vertical gaze

	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	0.0	0.6

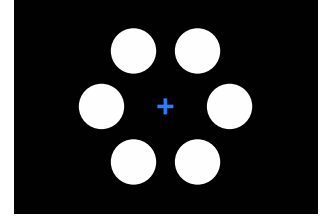
Table 2: Self-reported visual skills as defined by Fried-Oken et al. [9] of gaze-impaired participants included in this study. + skilled, — impaired, / severely impaired. Visual acuity was assessed using the logMAR scale (lower is better).



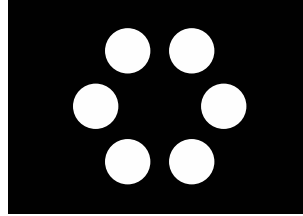
(a) A participant seated in a wheelchair in front of the stimulation laptop with EEG cap.



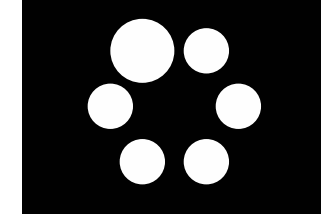
(b) Stimulation interface with 6 targets and fixation crosshair positioned for *overt* VSA.



(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

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 [14] implementation presented by Van Den Kerchove et al. [21]. 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. [21] 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. [21] 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 [9], 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 k Ω . 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 [25] and visual inspection. Next, the EEG was re-referenced to the average of mastoid electrodes TP9 and TP10, and independent component 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) [21] and block-Toeplitz linear discriminant analysis (tLDA) [26] classifiers, as well as the Riemannian approach XDAWNCov+TS+LDA [27]. 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

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 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

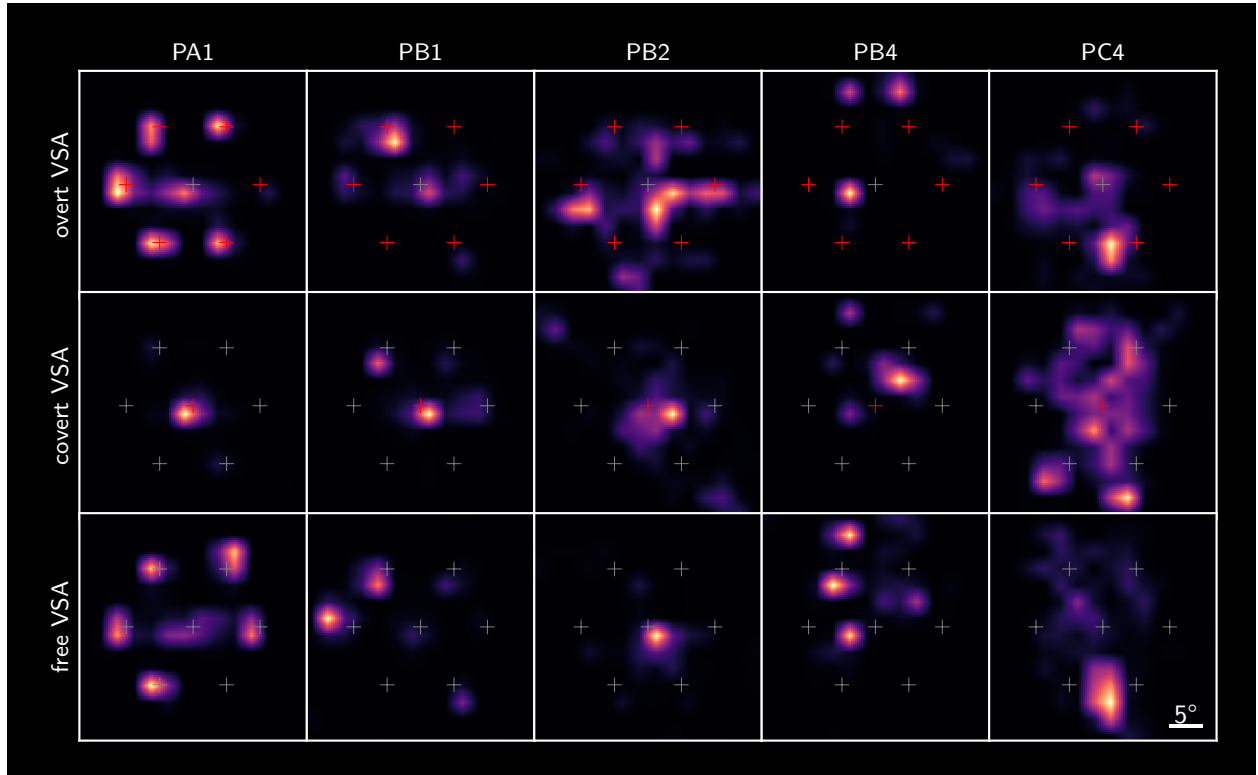


Figure 2: Distribution of the recorded gaze position during the experimental session in the three VSA conditions. Crosshairs represent stimulus positions, with positions cued during the given condition indicated in red. Subjects PB2 and PC4 preferred covert BCI operation, with PB2 resting gaze near the middle of the screen, and PC4 near the bottom. A high-resolution, non-downsampled figure is available as Additional file 1.

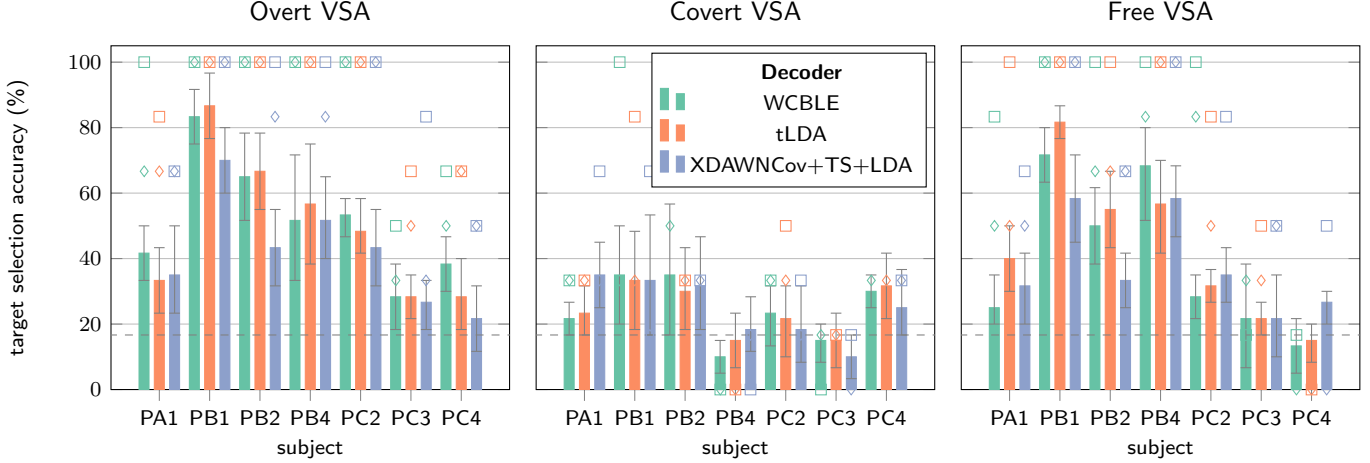


Figure 3: Decoding performance in different VSA settings reported as single-trial target selection accuracy (%). Accuracy in free VSA is generally on par with the overt VSA setting. In the covert VSA setting with central gaze fixation, accuracy is lower, but can be improved with the WCBLE decoder. Whiskers 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. ($\frac{1}{6}$).

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. A full table of results is available as Additional file 2. 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 XDAWNCov+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 accuracy 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 accuracy was 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

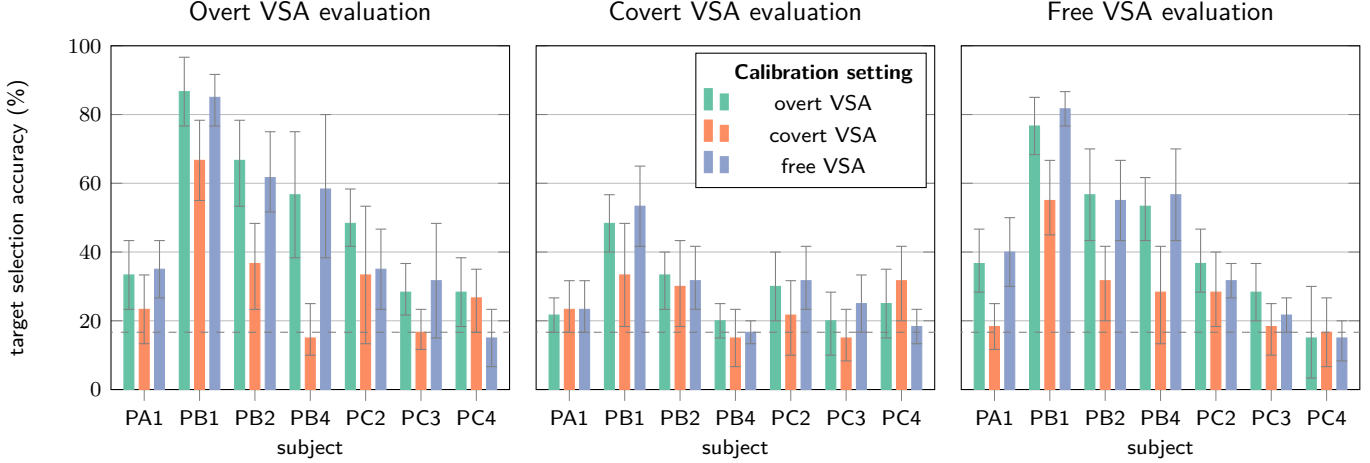


Figure 4: Decoding performance when calibrating the tLDA decoder in a given VSA setting, and evaluating it in another, reported as single-trial area under the receiver-operator characteristic curve. Whiskers indicate 95% confidence intervals determined using 10,000 bootstrapping repetitions. For participants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

training session session relying maximally on their residual gaze control. A full table of results is available as Additional file 3.

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.

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. [21], 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, 29, 21], 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 [30]. 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 on-line 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. Eye motor disability could also have been assessed more quantitatively and objectively [9], using, e.g., the Revised Coma Recovery Scale [31] or the NSUCO oculomotor exam [32], in order to relate them to the decoding or satisfaction results.

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 [33, 34, 35, 36]. 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 [35]. 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 [33]. 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 [9]. 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 [37, 38], 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.

Acronyms

AAC assistive and augmentative communication

ALS Amyotrophic Lateral Sclerosis

BCI brain-computer interface

368 **EEG** electroencephalography
369 **EOG** electrooculogram
370 **FRDA** Friedreich’s Ataxia
371 **ICA** independent component analysis
372 **ISI** inter-stimulus interval
373 **ITR** information transfer rate
374 **LiS** Locked-in Syndrome
375 **MS** Multiple Sclerosis
376 **RSVP** rapid serial visual presentation
377 **SSPGI** severe speech, physical and gaze impairment
378 **SSVEP** steady-state visually evoked potential
379 **TBI** traumatic brain injury
380 **tLDA** block-Toeplitz linear discriminant analysis
381 **UCD** user-centered design
382 **VSA** visuospatial attention
383 **WCBLE** Classifier-based Latency Estimation with Woody iterations

384 **Declarations**

385 **Ethics approval and consent to participate**

386 Ethical approval for this multi-center study was obtained from the Ethics Commission of the University
387 Hospitals Leuven (S62547), and prior informed consent to participate was obtained from all participants
388 included in this study.

389 **Consent for publication**

390 Prior informed consent for publication of the reported data was obtained from all participants included in
391 this study.

Availability of data and materials

The datasets generated and/or analysed during the current study are not publicly available due to the policies in agreement with the ethical approval to protect sensitive personal information, but are available from the corresponding author on reasonable request.

Competing interests

The authors declare no competing interests.

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Author’s contributions

AVDK conceptualized the work and performed the analyses presented this study, under supervision of HSM, FC and MMVH. JM assisted in data collection, conceptualization and data analysis. AW and MDM provided paramedical support in participant recruitment, care and communication. DG assisted in participant recruitment at the Univesity Hospitals Leuven NMRC under clinical supervision of PVD. ES supervised participant recruitment at TRAINM. EA provided clinical supervision during conceptualization, experimentation, supervised recruiting at Fondation Partage et Vie and contributed the neuro-ophthalmologic diagnoses. All authors read and approved the final manuscript.

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If you are an academic partner and received governmental or project funding during the project please let me know in order to complete this section.

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Additional files

1. Additional file 1

Format: portable network graphics file (.png)

Title: Heatmap of gaze location per VSA condition.

Description: High-resolution heatmap of the distribution of 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.

2. Additional file 2

Format: comma-separated values file (.csv)

Title: Decoding performance per patient. *Description:* Full table of decoding target selection accuracies per patient, decoder and VSA condition.

3. Additional file 3

Format: comma-separated values file (.csv)

Title: Cross-condition decoding performance per patient. *Description:* Full table of cross-validated, cross-condition decoding target selection accuracies per patient and decoder.

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A Clinical evaluation of participants

PA1 *Diagnosis:* 58 y.o., originally left-handed male diagnosed with bulbar-onset Amyotrophic Lateral Sclerosis (ALS) 2 years prior at age 56. Recently, symptoms started progressing more on the right side and resulted in immobility of the left limbs and partial immobility of the right limbs, but right arm and finger movement were possible, albeit with effort. *Presentation:* PA1 presented lying reclined in a hospital bed, the experimental setup was positioned on a movable folding table. *Communication:* Due to complete anarthria, PA1 communicated using vocal grunts and a text-to-speech assistive and augmentative communication (AAC) tablet operated with the right hand. *Eye movements:* He reported fatigue linked to his disease progression when visually fixating for prolonged times, but otherwise reported no eye movement abnormalities or visual defects.

PB1 *Diagnosis:* 41 y.o., originally left-handed male diagnosed with Friedreich's Ataxia (FRDA) 29 years prior, at age 12. Symptoms resulted in slowed, effortful body and limb movement and affected fine motor control, and most severely affected the left side which made him effectively right handed. *Presentation:* PB1 presented in an electric wheelchair, which was positioned in front of a table with the experimental setup. *Communication:* Verbal communication was possible, but dysarthria resulted in slowed, slurred

speech. He was able to effectively control a PC and a smartphone, but writing was difficult. *Eye movements:* PB1 reported impaired visual pursuit of moving targets and fatigue and discomfort fixating. Effectively, we noticed effort when making eye movements, which resulted in large muscular artifacts registered in the EEG and electrooculogram (EOG). Additionally, he reported minor nystagmus which we also noticed in the horizontal EOG.

PB2 *Diagnosis:* 43 y.o., right-handed female diagnosed with FRDA symptom-free at age 9, with symptom onset at age 12, 31 years prior to the experiment. Symptoms resulted in slowed, effortful body and limb movement and affected fine motor control. *Communication:* Dysarthric, characterized by large effort necessary to speak. Hand signaling was also often used, but also required effort. *Eye movements:* PB2 was affected by especially severe horizontal eye oscillations with onset 10 years prior to the experiment. Fixating was also fatiguing and uncomfortable, especially when not wearing glasses.

PB4 *Diagnosis:* 48 y.o., right-handed male diagnosed with FRDA 30 years prior at age 18. *Presentation:* PB4 was not strictly wheelchair-bound. *Communication:* Speech was relatively fluent, only slightly slurred, leading to mild dysarthria. *Eye movements:* Pursuit and fixation were impaired, as characterized by self-reported fatigue and discomfort. Nystagmus.

PC2 *Diagnosis:* 43 y.o., originally right-handed male diagnosed with Locked-in Syndrome (LiS) due to ischemic brain stem stroke 6 years prior, at age 37. He underwent a tracheostomy. *Presentation:* PC2 was seated in an electric wheelchair controlled by a caregiver, and his head was fixated in a headrest. This headrest contacted the EEG cap occipitally and centroporally, which interfered slightly with cap and electrode positioning and optimization. Additionally, heavy movement artifacts were noticed in the EEG due to the combination of breathing, aspiration, the headrest and maintaining correct positioning for the experiment. The EEG cap was held in place using a chest strap. *Communication:* PC2 was completely anarthric and had no preserved facial movement. He communicated with caregivers by responding to prompted letters and words with upwards eye movement signaling. Additionally, he sometimes made use of an emergency button which he could control with his left hand, the only extremity in which he had some residual control capability. *Eye movements:* Right eye: preserved vertical movement, paralysis of laterality to the right and to the left, which resulted in the inability to perform horizontal movements. Left eye: preserved vertical movement, adduction possible, abduction deficit. Deviation in the left eye resulting in diplopia, corrected by a prism glass. Self-reported tremors and fixation fatigue and discomfort.

584 **PC3** *Diagnosis:* 43 y.o., right-handed female diagnosed with hemorrhagic stroke 4 years prior, at age 39.
585 She was tetraplegic and underwent a tracheostomy. *Presentation:* PC3 was seated in an electric wheelchair
586 *Communication:* PC3 was completely anarthric, but had sufficient residual motor control to indicate letters
587 and symbols on a letterboard by pointing with movements of the right index finger and hand. *Eye move-*
588 *ments:* Right eye: complete ptosis When corrected, downward movement was preserved and incyclotorsion
589 was possible through preserved cranial nerve IV. Ophthalmoplegia in other directions. Left eye: Limited of
590 adduction, complete verticality, horizontal nystagmus. Intermittent nystagmus. Self reported involuntary
591 saccades and fixation fatigue or discomfort.

592 **PC4** *Diagnosis:* 54 y.o., originally right-handed male diagnosed with ischemic brainstem stroke 11 years
593 prior, at age 53. He is tetraplegic and underwent a tracheostomy. Symptoms most pronounced on left
594 side. *Presentation:* The tracheostomy resulted in frequent aspiration which interfered with the experiment
595 and recording. This and other factors related to the condition and positioning in the wheelchair resulted
596 in large and frequent muscular and movement artifacts in the EEG. Head bobbing When concentrating on
597 the experimental task. *Communication:* PC4 had sufficient residual motor control to indicate letters and
598 symbols on a letterboard by pointing with movements of the right index finger and hand. *Eye movement:*
599 A corneal abcess in the left eye affected it's motility and resulted in deviation. The left eye had poor vision
600 (only able to distinguish shapes) and could not be closed. The right eye was not affected. The deviation
601 resulted in fatigue and discomfort fixating. Hypermetropia.

this is self-
reported, of-
ficial oculo-
motor diag-
nosis needed