Visual ERP-based Brain-Computer Interfaces in patients with severe physical, speech and eye movement impairment: case studies

Arne Van Den Kerchove, Juliette Meunier, Alixe Willemssens,
Marie de Moura, Hakim Si-Mohammed, Etienne Allart,
Marc M. Van Hulle, François Cabestaing

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1 Introduction

Brain-computer interface (BCI) assistive technologies for communication [15] target individuals with severe speech and physical impairment (SSPI) [19]. Visual BCIs, which rely on the interpretation of visual stimuli by the user, offer several advantages in this context. They can work with non-invasive recording technology and can use rapid stimulation. This makes them well-suited for real-time communication tasks.

Yet, there is a large comorbidity between SSPI and eye motor impairment [6]. Impairments such as nystagmus (uncontrolled eye movements), diplopia (double vision), and ophthalmoplegia (eye paralysis) can significantly hinder the ability to use visual BCIs. These impairments make it difficult for BCI users to focus on or track visual stimuli accurately, reducing their performance with BCIs that rely on visual cues [14, 6, 18]. Unfortunately, it is again for this group that eye tracking solutions also perform poorly, making them more reliant on potential developments in BCI that do not rely on eye gaze.

Eye motor impairments are presumed to reduce performance in operating visual oddball BCIs (see **??** for an overview), 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 [22]. These interfaces either avoid visual stimulation or exploit some form of covert VSA, where the gaze and VSA do not coincide.

Several studies with visual oddball BCIs show that performance drops when not fixating the intended target [3, 26, 23], necessitating gaze-independent solutions. These studies build on the assumption that BCI users with severe speech, physical and gaze impairment (SSPGI) would feel comfortable operating an interface in pure covert VSA with central fixation. One could argue that a BCI that is only verified to work when central fixation is maintained could also be considered gaze-dependent. This does not account for the residual eye motor capabilities of most people with SSPI, the (dis)comfort they experience while performing gaze fixation and other confounding factors resulting from their eye motility.

It is a striking constatation that studies reporting on gaze-independent visual BCI with people with SSPI and eye-motor impaired are very few. Results are usually different from those obtained with healthy control participants in the lab, due to difference in capabilities, brain response, equipment and environment.

Lesenfants et al. [12] tested a BCI using gaze-independent steady-state visually evoked potential (SSVEP) in six participants with Locked-in Syndrome (LiS) yet only exceeded chance level accuracy in two. More recently, Peters et al. [20] performed a trial with two participants with late-stage Amyotrophic Lateral Sclerosis (ALS) and visual impairment. Their SSVEP interface was not optimized for gaze-independence, but the system showed high accuracy, outperforming an eye tracking alternative. It would be of interest to verify if such results can be replicated with participants with other conditions, and with a visual oddball BCIs.

Orhan et al. [17] and Oken et al. [16] tested the rapid serial visual presentation (RSVP) speller with individuals with LiS.

Severens et al. [24] evaluated the visual Hex-o-Spell [26] 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 suggested that participants were performing overtly. Participants with ALS also had a substantially lower accuracy than healthy controls (58% vs. 88%).

Our previous study, presented in **??** also used the visual Hex-o-Spell interface [27]. This work partially accounted for the idea that BCI users with SSPGI might not fully rely on central gaze fixation and evaluated settings that are not strictly dependent on this. We showed gaze-independent performance can be improved in healthy subjects using a suited decoding strategy that accounts for latency jitter in covert VSA responses. Yet, there is a strong need for verification of these results in an applied setting with people with SSPI.

Eventually, one of the end goals of this research line is to develop gaze-independent BCI for people that are fully locked-in and have no option left than to use a BCI. However, this group is very small and it is often a challenge to recruit them into a study and perform experiments with them [28]. 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. Therefore, we aim to apply the concepts from earlier work and literature to people with SSPI and various degrees of motor impairment in a visual oddball BCI. The objectives of this case study are as follows: 1. Explore capabilities and experienced comfort of individuals with SSPGI, when operating a visual BCI, 2. evaluate the performance of a gaze-independent visual BCI for this group, 3. verify if this performance can be improved with a suitable decoding strategy.

2 Materials & methods

2.1 Recruitment

Participants were recruited across the Neuromuscular Reference center at University Hospital Leuven (Leuven, Belgium), TRAINM Neuro Rehab Clinics (Antwerp, Belgium), the Neurorehabilitation Unit at University Hospital Lille (Lille, France), and a specialized care home (France). Experiments were performed under the supervision of their treating physician. Participants were recruited based on the following criteria. To qualify for inclusion, 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. [28],

3. have limitations to the extent or comfort of their eye motor control

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. are currently using specific psychoactive medications or substances that could affect the outcome.

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, which 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. Vision was assessed using a LogMAR chart [2].

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 stroke. We refer to **??** for a short description of these conditions. Table 1 lists the included participants and their diagnoses.

2.2 Visual skills and eye tracking and eye motor examination

Self-reported eye motor and visual abnormalities were recorded according to the relevant visual BCI skills presented by Fried-Oken et al. [6]. These 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.

As an objective metric, we implemented and performed the automated NeuroEye eye movement test proposed by Hassan et al. [9] using calibration-free eye tracking to check if it revealed any further eye motor abnormalities. This was not the case.

Finally, we also recorded gaze position throughout the experimental session to register the participant's gaze relative to the stimulated BCI targets.

[1]See **?? ??**.

[2]"With minor degree of impairment, we refer to patients who had only slightly impaired limb movement and normal speech. Under the category moderate impairment, we summarized those patients with restricted limb movement (wheelchair-bound) and unaffected speech or intact limb movement without speech. […]Patients who were almost tetraplegic with restricted speech were considered majorly impaired. Categories four and five were the LIS and the CLIS, respectively." [10]

2.3 BCI stimulation

The BCI stimulation procedure was based on the Hex-o-Spell [26] implementation presented by Van Den Kerchove et al. [27]. Similar to this study, the task consists of counting the flashes of a cued target among 6 round, flashing targets laid out in a hexagonal pattern in the field of view of the user. We refer to **??** for implementation details.

Three different VSA settings were explored. In the overt VSA setting, the participant was instructed to fixate on the cued target or try 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. [27] 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 SSPI [6], the number of blocks was decreased to 6 per VSA setting. Inter-stimulus interval (ISI) was increased to 200±50 ms to decrease task difficulty. The experiment also started with a training block in each condition, where the participant was instructed with feedback on their performance to ensure they understood and were able to perform the task.

2.4 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 electroencephalography (EEG). Eye tracking was performed throughout using the To-

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	brainstem stroke	43	M	R	anarthric	yes	prompting +eye movement	2	4
PC3	brainstem stroke	43	F	R	anarthric	yes	letterboard	2	3
PC4	left cerebellar stroke (trombosis of the basilar artery)	54	M	R	anarthric	yes	letterboard	2	3

Table 1: Included participants with their diagnosis and capabilities. Trach.: underwent a tracheostomy, W: classification according to Wolpaw et al. [28][1], KB: classification according to Kübler and Birbaumer [10][2].

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

Table 2: Visual skills of the included participants. Visual BCI skills [6] were assessed with a combination of self-reported issues by the subject and the NeuroEye [9] test. +skilled, -impaired, - -severely impaired. logMAR: lower is better.

bii X2-30 Compact (Tobii Technology AB, Sweden) portable eye tracker placed at the bottom of the laptop screen.

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 [5] 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 in order to meet the assumptions.

Eye tracking data was cleaned by fusing left and right gaze into one channel for the horizontal and 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 of the employed classifiers.

Figure 1: A participant with the stimulation and recording setup.

2.5 BCI decoding

We evaluated the recorded data using the Classifier-based Latency Estimation with Woody iterations (WCBLE) [27] and block-Toeplitz linear discriminant analysis (tLDA) [25] classifiers, as well as the Riemannian approach XDAWNCov+TS+LDA [4]. 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 performance. Decoding scores were obtained using 6-fold cross-validation where folds corresponded to stimulation blocks.

3 Results

3.1 Visual skill and eye tracking analysis

Table 2 details the eye motor impairments and vision of the included participants. 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. 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.

Given these information, we aimed to shed more light on the actual capabilities of individuals with SSPGI regarding performing overt VSA and central gaze fixation, as well as to investigate how relevant these two settings are when the gaze is not cued. Figure 2 maps gaze position relative to the stimuli across conditions. These results should be interpreted with care, as the eye tracker to some degree relies on functioning eye motility. The participant's position relative to the eye tracker might have shifted throughout the experimental session despite our best efforts, e.g., because they needed aspiration of their tracheostomy.

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 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.

It was technically impossible to register 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 single-trial area under the receiver-operator characteristic curve (ROC-AUC) in the evaluated VSA settings for the different decoders.

In the overt VSA setting, the evaluated decoders performed similarly on average (WCBLE 75.58%, XDAWNCov+TS+LDA 74.24%, tLDA 75.99%). In the covert VSA setting with cued central gaze fixation, performance deteriorated, but WCBLE significantly improved performance over the base classifier tLDA in this condition (WCBLE 62.49%, XDAWNCov+TS+LDA 59.42%, tLDA 59.05%). Decoding performance for this task was at chance level for participants PB4 and PC3.

However, WCBLE did not improve tLDA performance in the free VSA setting, but XDAWNCov+TS+LDA performance was slightly lower here (though not significantly). (WCBLE 74.15%, XDAWNCov+TS+LDA 71.88%, tLDA 74.27%). More interestingly, we noticed that performances of the decoders in free VSA were close to those in the overt VSA. A substantial decrease in performance from the overt setting to the free setting was observed for subjects PC3 (WCBLE: 70.31>62.14 %, XDAWNCov+TS+LDA: 65.78>62.18 %, tLDA: 70.49>63.76 %) and PC4 (WCBLE: 65.56>55.71 %, XDAWNCov+TS+LDA: 62.02>54.24 %, tLDA: 66.12>57.08 %). For PB2, who also relied on covert VSA during the uncued free VSA according to gaze tracking setting, the decrease in performance was also present, but not as substantial (WCBLE: 82.76>78.88 %, XDAWNCov+TS+LDA: 80.74>77.99 %, tLDA: 83.21>78.84 %).

3.3 Cross-condition calibration

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

Figure 4 shows that, on average, covert VSA decoding improved when training with overt VSA. This was especially true for participants PA1, PB2, and PC3. Note that, according to eye tracking data, participants PB1, PB4, and PC4 did not always perform cued central gaze fixation in the covert VSA setting, which might have affected the results.

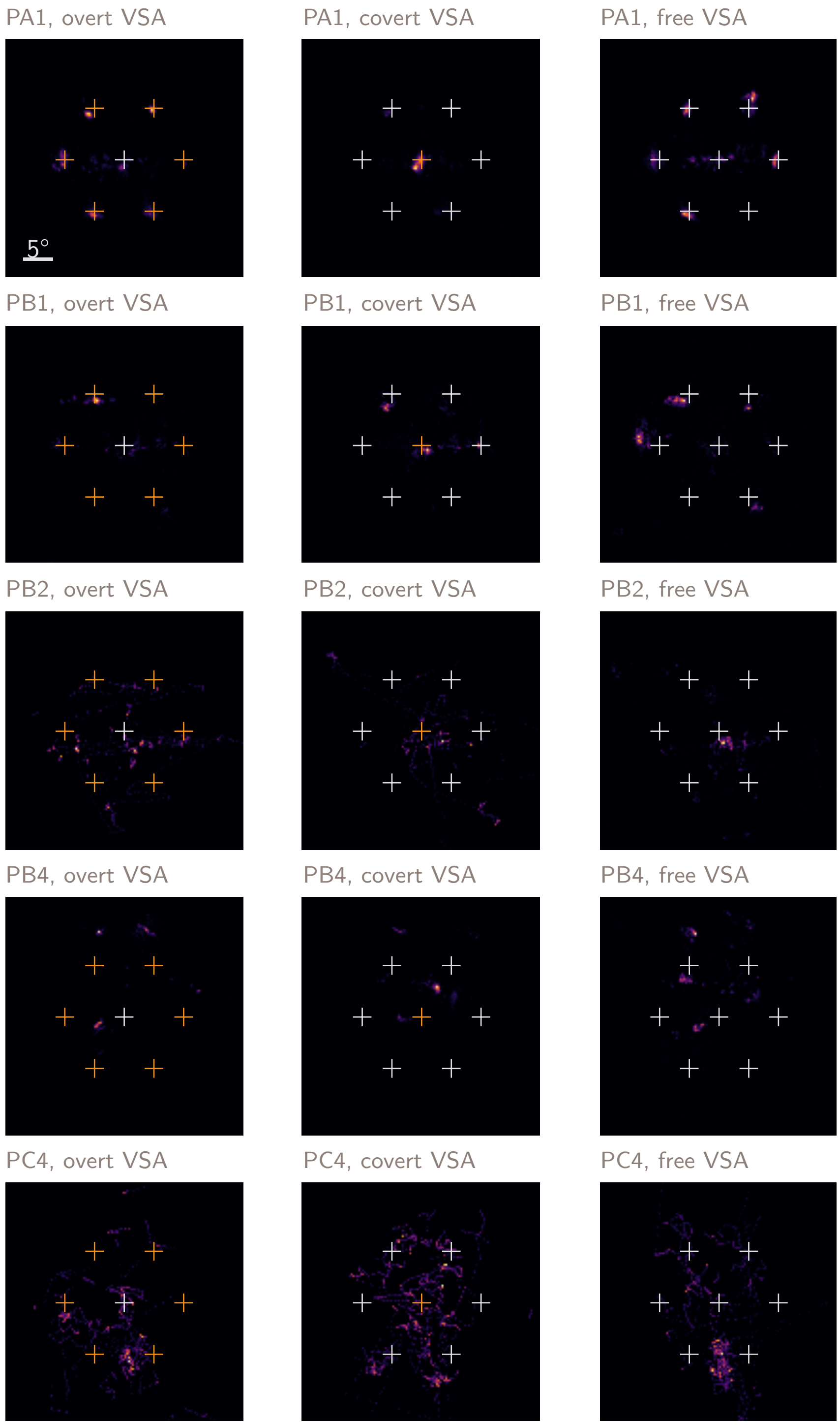

Figure 2: Distribution of the recorded gaze position during the experimental session in the three VSA conditions. Crosshairs represent stimulus positions, with the orange ones cued during the given condition. Subjects PB2 and PC4 preferred covert BCI operation, with PB2 resting gaze near the middle of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

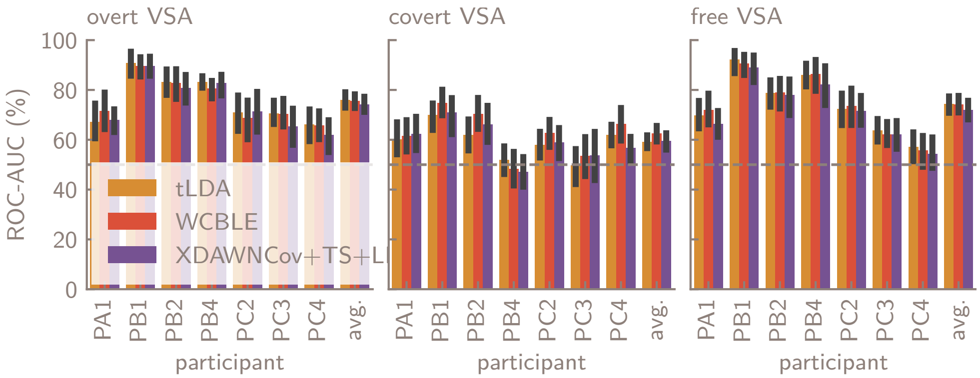

Figure 3: Decoding performance in different VSA settings reported as single-trial ROC-AUC. Free VSA is generally on par with performance in the overt VSA setting. Performance in the covert VSA setting with central gaze fixation is lower, but can be improved with the WCBLE decoder. 95% confidence intervals were calculated using 1000 bootstrapping repetitions.

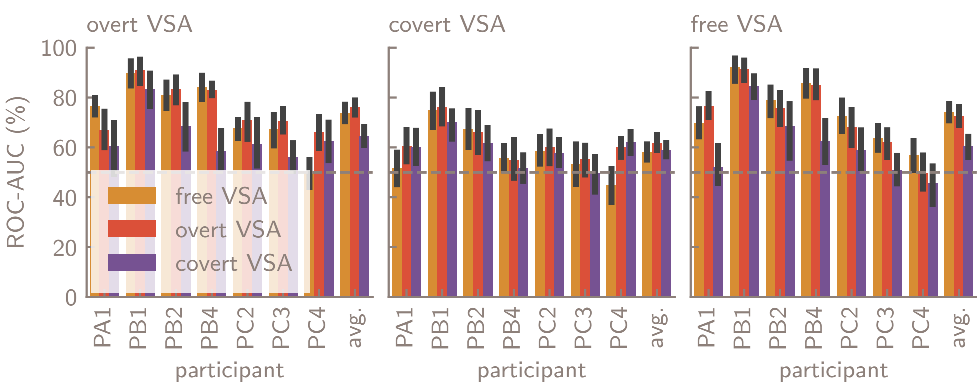

Figure 4: Decoding performance when calibrating the tLDA decoder in a given VSA setting, and evaluating it in another, reported as single-trial ROC-AUC. For participant PA1, free VSA performance improved when calibrated with overt gaze fixation. For participants PA1, PB2, and PC3, performance in the covert VSA setting with central gaze fixation improved when calibrating with overt gaze fixation.

4 Discussion

4.1 Gaze-independent operation & decoding

Due to the heterogeneous nature of the participants' conditions, 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 would like to 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 from Van Den Kerchove et al. [27] presented in **??**, 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 individuals with SSPGI.

Contrary to our assumptions, however, we have shown that this 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 [21, 1, 27], 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 performance 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 performance 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 but the most severe gaze impairments will likely retain some degree of gaze direction in visual BCI operation, which can drastically boost performance. Subject PB2 exemplifies this: his free VSA performance is on par with his overt VSA performance, although 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 calibration presented in section 3.3, which show that leveraging residual eye motor control to fixate targets during the calibration phase can improve performance 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 calibration phase leaves the user free to operate in the manner that is most comfortable for them 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 Limitations

Despite results that prompt interesting reflections on gaze-independent BCI approaches, there are some limitations to the presented results that need to be addressed in current and future work.

First and foremost, this study works with a limited sample size, which does not represent the full spectrum of individuals with SSPI and 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.

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. To properly contextualize performance results, they should be coupled with metrics evaluating the user's requirements with a measure of usability, comfort and perceived effort, like the NASA Task Load Index [8] and other metrics proposed in the user-centered design framework for BCIs [11]. Performance might, after all, be traded off for user comfort. Eye motor disability could also have been assessed more objectively [6], using, e.g., the Revised Coma Recovery Scale [7] or the NSUCO oculomotor exam [13].

Finally, the stimulation procedure parameters from Van Den Kerchove et al. [27] were adapted to make the counting task accessible to the BCI users with SSPGI. However, the number of repetitions and ISI were not optimized to achieve maximal information transfer rate (ITR). An interface that aims to maximize ITR could necessitate more and faster gaze redirections, which might result in different conclusions regarding the comfort and the effect of visual skill.

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