Towards solving of the Illiteracy phenomenon for VEP-based brain-computer interfaces

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Abstract
Brain–Computer Interface (BCI) systems use brain activity as an input signal and enable communication without requiring bodily movement. This novel technology may help impaired patients and users with disabilities to communicate with their environment. Over the years, researchers investigated the performance of subjects in different BCI paradigms, stating that 15%–30% of BCI users are unable to reach proficiency in using a BCI system and therefore were labelled as BCI illiterates. Recent progress in the BCIs based on the visually evoked potentials (VEPs) necessitates re-considering of this term, as very often all subjects are able to use VEP-based BCI systems. This study examines correlations among BCI performance, personal preferences, and further demographic factors for three different modern visually evoked BCI paradigms: (1) the conventional Steady-State Visual Evoked Potentials (SSVEPs) based on visual stimuli flickering at specific constant frequencies (fVEP), (2) Steady-State motion Visual Evoked Potentials (SSmVEP), and (3) code-modulated Visual Evoked Potentials (cVEP). Demographic parameters, as well as handedness, vision correction, BCI experience, etc., have no significant effect on the performance of VEP-based BCI. Most subjects did not consider the flickering stimuli annoying, only 20 out of a total of 86 participants indicated a change in fatigue during the experiment. 83 subjects were able to successfully finish all spelling tasks with the fVEP speller, with a mean (SD) information transfer rate of 31.87 bit/min (9.83) and an accuracy of 95.28% (5.18), respectively. Compared to that, 80 subjects were able to successfully finish all spelling tasks using SSmVEP, with a mean information transfer rate of 26.44 bit/min (8.04) and an accuracy of 91.10% (6.01), respectively. Finally, all 86 subjects were able to successfully finish all spelling tasks with the cVEP speller, with a mean information transfer rate of 40.23 bit/min (7.63) and an accuracy of 97.83% (3.37).

1. Introduction

Brain–Computer Interface (BCI) is a revolutionary technology that can be mainly used as a new system, or additional tool, that can allow impaired patients and users with disabilities to interact with their environment via brain signals without the need for muscular activity [1, 2]. BCIs function by monitoring human brain activity, usually non-invasively by the utilisation of electroencephalography (EEG), and converting it into computer commands for real-time control of software and external devices [3].

In comparison to other BCI paradigms, BCIs based on visual evoked potentials (VEPs) are very robust, can generally be realised with less EEG electrodes, and yield the fastest performance practically without any BCI training [4–6].

The Steady-State Visual Evoked Potential is characterised by positive and negative fluctuations in the EEG signal, which are responses to a visual stimulus. For example, a blinking light, a picture that appears/disappears, or a specific distinct visual pattern is presented to the BCI user. As the subject’s eyes are focused on the visual stimulus, SSVEP signals are induced in the EEG recording in the form of voltage oscillations primarily from the visual cortex, located in the occipital region of the brain [7]. For BCI purposes, the SSVEP signals are further processed to detect their...
unique features, such as frequency, amplitude, and nowadays also the phase [4, 8, 9].

When the external visual stimulus is flickering at a fixed constant frequency, an SSVEP is elicited with a peak frequency corresponding to the stimulus (as well as its harmonics). These peaks are primarily observed in the visual cortex which is located in the occipital region of the brain, provided that the eyes of the subject are focused on the stimulus [10]. Usually, a frequency analysis method, such as Fast Fourier Transform (FFT), is used to detect the stimulation frequency [11, 12]. In a typical SSVEP system, taking as an example the spelling application, the targets can be individual letters or groups of characters or command boxes [2]. Each target flickers with a unique constant frequency. This SSVEP technique is straightforward to implement and is nowadays commonly named as frequency-modulated Visual Evoked Potential (fVEP) [13].

Another well-known type of VEP is the so-called code-modulated Visual Evoked Potential (cVEP) [14, 15], which was originally described in [16]. Instead of using a constant flickering frequency, the stimulus presented to the user is a pseudo-random swapping of orthogonal patterns, mainly m-sequences, each associated with a specific binary code pattern, that determines whether the stimulus is displayed or not displayed [14, 17, 18]. Modern cVEP implementations are mostly designed for high-speed communication [6, 19].

One of the main problems usually connected to the traditional VEPs is the considerable level of the visual fatigue caused by the prolonged use of intense light stimulation, based on flickering or contrast-change related paradigms, with a consequent reduction of recognition accuracy. Several attempts have been made recently in order to minimise the effect of visual fatigue. In 2012, Xie et al proposed the steady-state motion visual evoked potential (SSsVEP)-based BCI paradigm that relied on human perception of motions, where four Newton’s rings with the oscillating expansion and contraction motions served as visual stimuli, instead of the regular flickering [20]. Further improvements of this paradigm were published recently, generally confirming that movement patterns of included contraction and expansion produced less discomfort to the BCI users [21, 22].

However, over the years, researchers investigated the subject’s performance for different BCI paradigms, including VEPs, which are the main focus of the herein study. The main question was how many (and what kind of) people could use a specific type of BCI [23–27]. These studies tested three major BCI paradigms [3], based on P300, motor imagery (MI) or Steady-State Visual Evoked Potential (SSVEP), with different demographic groups. Thus, a condition known as BCI illiteracy was introduced for those who failed to use the systems proficiently. It was usually defined by a low control performance of less than 70% [28], in a predefined time period. Across a variety of BCI paradigms in the BCI studies, researchers estimated that 15%–30% of BCI users cannot achieve this level of control and can, therefore, be labelled as BCI illiterates [29, 30].

Shortly after the initial introduction of this term, already in 2010, Allison and Neuper [31] identified various issues with BCI illiteracy, including inconsistent proficiency thresholds, and inadequate differentiation of the causes for weak BCI performance. They also discussed making BCI illiteracy more rigorous as a category, for example, outlining categories of causes of illiteracy. According to Myrden and Chau [32], changes in attention level, fatigue, or frustration may cause the same individual to move in and out of the illiteracy category. Social factors as well, such as emotional responses, interactions, and social cues, might affect the user’s BCI performance [33].

Moreover, M. Thomson in [34] presented the argument that BCI illiteracy is an inadequate concept for explaining many cases of poor user performance in BCI systems. This work also continues to explain that users may be classified as illiterate if their performance does not meet a certain threshold. In essence, they do not reach a certain level of performance, or they do not reach it fast enough within the confines of the experiment, which is not a direct quality of the users themselves. Additionally, some research supports the idea that many instances described as BCI illiteracy may be due to the structure of current BCI training protocols [35].

In general, when BCI illiteracy is studied, researchers often do not have a reasonable justification for its occurrence. However, they tend to label the user as illiterate even though the confusion might be caused by the system and neglect the possibility that it is possible that an individual who performed flawlessly in one BCI may be labelled as illiterate in another [36].

All the previously mentioned BCI illiteracy studies were conducted many years ago, mainly using one of three well-known major BCI paradigms. According to our knowledge, none (or very few, e.g. just to mention the very recent study [37] analysing the SSsVEP differences between two groups of five subjects each, the literates and illiterates) of the studies investigated the illiteracy phenomena while controlling the BCI with modern VEP paradigms. Moreover, previous studies with a large number of participants reported results from one VEP paradigm only. However, selecting the best VEP paradigm individually might reduce the occurrence of the BCI illiteracy.

Therefore, although the term ‘BCI illiteracy’ is generally misleading, because it suggests the inability to control the BCI lies with the person, which is very often not the case, it seems to be still broadly used by the BCI community, as e.g. [37–39]. The other related term ‘BCI inefficiency’ suggested for this phenomenon later [40] was not properly adopted by the scientific community, probably due to the fact that it was published in proceedings within the scope of a conference which are still not broadly indexed by scientific
The presented study compares the BCI performance of three VEP paradigms: 1) the conventional SSVEP based on visual stimuli flickering at specific constant frequencies, fVEP, 2) Steady-State motion Visual Evoked Potential, SSmVEP, and 3) code-modulated Visual Evoked Potentials, cVEP. For the comparison between these three different code patterns, an earlier developed spelling application, so-called three-steps-speller was used, which requires three selections to be made to select a letter [42]. Three-step-spellers are very robust; they require four different visual stimuli only and are well-tested and reliable, which is needed for comparison of the differences in the performance depending on factors subject to investigation [43].

This study was carried out with 86 able-bodied participants. Selecting the optimal paradigm for each user should also include the user-friendliness of the paradigm. For this reason, we compared the different modern VEP-based BCI paradigms against each other, not only in the form of objective measurements of achieved accuracies and information transfer rates but also stating the subjective preferences of the study participants, collected in the form of questionnaire results. While a high number of participants alone is not sufficient to prove a definitive solution for BCI illiteracy, results indicate an adequate update of the estimated rate of BCI illiteracy reported in the literature.

2. Materials and methods

2.1. Participants

The experiment was approved by the ethical committee of the medical faculty of the University Duisburg-Essen, Germany. All subject information for the data analysis of the study was stored pseudonymously in the form of subject numbers only; results can not be traced back to the individual participant. Written informed consent in accordance with the Declaration of Helsinki was given by each participant before taking part in the experiment, and each received financial compensation for participating. Spectacles were worn when required. The experimental session lasted on average 90 minutes and subjects had the opportunity to opt-out during the experiment. 89 able-bodied participants visited our BCI lab. Of the 89, three subjects dropped out for personal reasons, hence their data were removed from further calculations. Information about the remaining 86 participants is shown in table 1.

2.2. Hardware

The used computer (Dell Precision 3630 Tower, Microsoft Windows 10 Education) was equipped with Intel processor (Intel Core i7-8700K, @3.70 GHz), 16 GB RAM, and an NVIDIA GeForce GTX 1080 graphics card. The user interface was presented on a liquid crystal display monitor (Acer Predator XB252Q, 1920 × 1080 pixel, 240 Hz refresh rate).

All 16 recording channels of the EEG amplifier (g. USBamp, Guger Technologies, Graz, Austria) were used; passive Ag/AgCl electrodes were placed according to the international 10/5 system of electrode placement (see [44] for more details): Fz, P3, P4, Pz, PO3, PO4, PO7, PO8, O1, O2, O1, Oz, and O10. Although good results can already be achieved with a lower number of electrodes, we used 16 EEG electrodes to enable faster and more robust selections with the BCI. The common reference electrode was placed at Cz and the ground electrode at AFz. A digital band pass filter (with cut-off frequencies 2 and 100Hz) and a notch filter (around 50 Hz) were applied. The sampling frequency, Fs, was set to 600 Hz. Standard abrasive electrolytic electrode gel was applied between the electrodes and the scalp to bring impedances below 5 kΩ.

2.3. Spelling interface

In the BCI system used in this study (so-called three-steps-speller), which requires three selections to be made to select a letter, for more details, please refer to [42], four circular targets (230 × 230 pixel), each representing one selection option, were presented to the user. The GUI consisted of 27 characters (26 letters and one underscore/space character) divided into three boxes (nine characters each, ‘A-I’, ‘J-R’, ‘S-Z’ + space). By selecting a letter group, the associated characters were presented in groups of three in the second step and individually in the third step, as illustrated in figure 1.

In the first step, the user selected one group of characters, e.g. ‘A-I’. The letters were then divided into three sub-groups, e.g. ‘ABC’, ‘DEF’, ‘GHI’, and a ‘Back’ command. After a selection in the second step the content of the sub-group were again distributed over the circles, e.g. ‘A’, ‘B’, ‘C’, and a ‘Back’ command. In the third step, each character could be selected individually, e.g. ‘B’ and afterwards the GUI switched back to the first view (3 groups of letters).
Table 1. Subjects information summary table.

| Age (Years ± SD) | Gender | BCI Experience | Vision correction | Handedness |
|------------------|--------|----------------|-------------------|------------|
|                  | Male   | Female | Neutral | Yes | No | not needed | needed/used | needed/not used | Left handed | Right handed |
| 25.24 (4.16)     | 58     | 27     | 1       | 42  | 44 | 60         | 22          | 4            | 9           | 77          |
2.4. Experimental procedure

The participants were seated approximately 50 cm from the screen. The experiment consisted of three sessions (one for each stimulus paradigm): an fVEP session, a cVEP session and an SSmVEP session, each consisting of a recording stage and an on-line copy-spelling stage as well as the corresponding questionnaire. The sessions were randomly permuted to avoid the order of sessions from affecting the averaged performance measures.

In the recording stages, several trials of EEG data corresponding to each of the four stimuli were collected. The recording was grouped in six blocks, corresponding to each of the four stimuli were collected. The recording stage and an on-line copy-spelling stage as well as the corresponding questionnaire. The sessions were randomly permuted to avoid the order of sessions from affecting the averaged performance measures.

In the recording stages, several trials of EEG data corresponding to each of the four stimuli were collected. The recording was grouped in six blocks, \( n_b = 6 \), and the participant fixated once upon each of the \( K = 4 \) targets.

In total, \( n_b \cdot K = 24 \) trials were collected. Each trial consisted of three stimulation cycles and the trial duration depended on the used paradigm (3.15 s for the cVEP paradigm and 3 s for the fVEP and SSmVEP paradigms).

At the beginning of a recording block, the users pressed the space bar to initiate the flickering and the data recording. A green frame indicated the target the user needed to gaze at during each trial.

In between trials, the flickering paused for one second and the next target was highlighted. In between blocks (i.e. after each fourth trial) the user could rest. The data collected during these recordings were used for classification as described later. Figure 2 shows the maximum Canonical-correlation analysis (CCA) correlation coefficients, \( \rho_i \), of all recorded EEG channels. This figure presents the data for participant 10, her/his responses recorded during the first stimulation cycle. The reference signal was the \( \sin(f) + \cos(f) \) signal (without harmonics) where \( f \) ranged from 6 to 35 Hz with \( \Delta f = 0.1 \) Hz. From these training data we can already clearly see the high correlation of used stimulation frequencies and the fVEP and SSmVEP recordings.

After this initial recording stage users were asked about their subjective opinions regarding the current paradigm; how relaxing and comfortable it was.

Thereafter, the on-line copy-spelling stage started with a brief familiarisation run, where participants learned the letter arrangement of the spelling interface and experimenters adjusted system parameters, more specifically, the classification thresholds and minimal classification time windows were adjusted to reduce misclassifications. The individual thresholds, \( \beta \), were manually adjusted while performing a few selections and confirming with a short spelling task or selecting each target at least twice.

After that, four copy-spelling tasks were performed. The words BCI, BRAIN, POWERFUL and an own choice word of at least five letters were spelled for each VEP modality. Possible errors needed to be corrected by gazing at the far right target representing the UNDO function.

The copy spelling tasks (BCI, BRAIN, and POWERFUL) were chosen so that the number of selections corresponding to each target was equal after spelling all three words during the optimal run without errors (the ‘Back’/‘Delete’ target was only used in case of errors). For all three copy spelling words, this resulted in 16 selections necessary for each of the first three targets in each session. Since the stimulus frequencies of each target were fixed, if the copy spelling tasks required the use of a specific target more often than the other two targets, we would have risked bias. For example, response to lower frequency flickering can be stronger for some users, so if a task only required use of the lowest frequency stimulus, we could get artificially increased performance for these users.

After every selection, audio (name of the selected command/letter) and visual feedback (the size of the selected box increased for a short time) were provided. During the entire copy-spelling experiments, progress bars displayed the current certainty level of the associated target on top of it.

After the spelling tasks, users were asked once again about their opinions about each individual speller used.

2.5. Questionnaire

The questionnaire for each paradigm consisted of the same nine questions or rather scales. Users had to assess their impression on the system on the scale. Two
questions had to be answered after the training phase but before the spelling tasks. The remaining questions were answered after the spelling tasks.

All questions required an answer on a Likert scale from 1 to 7, where one corresponded to complete disagreement with one term, and seven corresponded to complete agreement with the opposite of the term. The terms the users had to evaluate before the spelling tasks were relaxed versus exhausting, and comfortable versus annoying. These questions were selected to gather subjective opinions about visual fatigue caused by the stimuli.

After the spelling tasks, the further seven terms were efficient versus inefficient, clear versus confusing, supportive versus obstructive, exciting versus boring, inventive versus conventional, enjoyable versus annoying, and fast versus slow. These questions addressed the usability of the interface and the system itself. The questionnaire was inspired by the User Experience Questionnaire (UEQ) presented in [45].

2.6. Stimulus paradigms

In the following, the stimulus design and signal classification for each of the three stimulus paradigms are explained.

2.6.1. fVEP

2.6.1.1. Stimulus design

The stimulus design for the fVEP paradigm was realised using the hybrid frequency and phase coding approach (see, e.g., [46]): each selectable target was represented by a specific frequency \( f \) and phase \( \Phi \).

The flickering pattern was realized by sinusoidally modulating the target’s transparency (see, e.g. [4]). The stimulus sequence for the \( i \)-th target was calculated as:

\[
c_i(t) = \frac{1}{2} \left( 1 + \sin \left( 2\pi f_i \frac{t}{r} + \Phi_i \right) \right), \quad t = 0, 1, \ldots,
\]

yielding values in the range from 0 to 1.

So-called alpha compositing (the combination of an image with the background), was used to modulate the transparency of the BCI target in accordance to this sequence. The alpha channel of the RGBA colour space indicates how opaque a pixel is (\( \alpha = 0 \), corresponds to full transparency and \( \alpha = 1 \) corresponds to no transparency). As the background color of the user interface was black, the target color was ‘black’ if \( c_i(t) = 0 \) and ‘white’ if \( c_i(t) = 1 \).

In this study, the frequencies \( f_0 = 8 \), \( f_1 = 10 \), \( f_2 = 12 \), \( f_3 = 15 \) Hz, and phases \( \Phi_0 = 0 \), \( \Phi_1 = 0.25 \), \( \Phi_2 = 0.5 \), and \( \Phi_3 = 0.75\pi \), were used to calculate \( c_i \). These frequencies were chosen as they are dividers of the monitor refresh rate \( r = 240 \) Hz. The typical repetition period of the frequencies was 1 s.

Stimulus presentation and data acquisition were synchronised using two independent timers (one in the program thread dedicated to stimulus acquisition and another in the thread dedicated to the stimulus presentation) [47]. For the stimulus presentation the G-Sync technology was disabled, instead, the fixed
refresh-rate (240 Hz) setting was used. Thanks to the fast refresh rate of 240 Hz, the content of the screen is drawn in 4.16 ms as compared to other studies, where a standard 60 Hz refresh rate is used resulting in 16.66 ms.

2.6.1.2. Classification
For the IVEP system, spatial filters were created with the data collected during the recording stage. In this respect, CCA [48] was applied to the training trials. In general, CCA can be applied to two multi-dimensional variables $X \in \mathbb{R}^{n \times m}$ and $Y \in \mathbb{R}^{n \times q}$ in order to analyse their relationship. CCA searches weights $w_x \in \mathbb{R}^m$ and $w_y \in \mathbb{R}^q$ that maximize the correlation, $\rho$, between $x = X^T w_x$ and $y = Y^T w_y$ by solving

$$\max_{w_x,w_y} \rho(x, y) = \frac{w_x^T X Y^T w_y}{\sqrt{w_x^T X X^T w_x} \sqrt{w_y^T Y Y^T w_y}}. \tag{2}$$

Here, the CCA weights, used as a spatial filter in the on-line spelling, were constructed as follows. Each training trial was stored as a matrix $m \times n$, where $m$ denotes the number of signal channels (here $m = 16$) and $n$ denotes the number of samples (here, three 1 s stimulus cycles, i.e., $n = 1 \times F_s \times 3 = 1800$). In total, 24 of such trials $T_{ij} \in \mathbb{R}^{m \times n}$, $i = 1, \ldots, K$, $j = 1, \ldots, n_b$, were recorded.

For each target, individual templates $X_i \in \mathbb{R}^{m \times n}$ and filters $w_i$ were determined ($i = 1, \ldots, K$). For the generation of spatial filters, the two matrices were constructed,

$$\tilde{T}_i = [T_{i,1}, \ldots, T_{i,n_b}] \quad \text{and} \quad X_i = [\tilde{X}_i, \tilde{X}_i, \ldots, \tilde{X}_i],$$

where $\tilde{X}_i$ represents the average of the $n_b$ trials corresponding to the $i$-th class. Inserting these two matrices into (2) yielded the filter vectors $w_i = w_i$, $i = 1, \ldots, K$.

The on-line classification was performed if a new data block was added to a data buffer $Y \in \mathbb{R}^{m \times n}$ with dynamically increasing samples.

For target identification, the data buffer $Y$ was compared to reference signals $R_i \in \mathbb{R}^{m \times n_i}$, $i = 1, \ldots, K$, which were constructed as sub-matrix of the corresponding template $X_i$. That is to say, $R_i$ was constructed as submatrix of $X_i$ build from rows $1, \ldots, m$ and columns $1, \ldots, n_i$. Correlations $\lambda_k$ between the reference signals and the data buffer were calculated as

$$\lambda_k = \rho \left( \begin{bmatrix} Y^T w_1 \\ \vdots \\ Y^T w_K \end{bmatrix}, \begin{bmatrix} R_i^T w_1 \\ \vdots \\ R_i^T w_K \end{bmatrix} \right), \quad k = 1, \ldots, K. \tag{4}$$

The classifier output $C$ was then determined as

$$C = \arg \max_{k=1,\ldots,K} \lambda_k. \tag{5}$$

A sliding window mechanism was integrated for on-line spelling. BCI outputs were only performed if a threshold criterion was met. The EEG amplifier transferred data blocks in chunks of 30 samples (every 0.05 s, as the sampling rate was set to 600 Hz). For the sliding window mechanism, it was required that the number of samples per block is a divider of the cycle length, (630 samples for the cVEP paradigm and 600 samples for the IVEP and SSmVEP paradigm, respectively). The data buffer $Y$ was updated dynamically whenever new data was added; i.e., $n_b$ extended incrementally by 30 samples as long as $n_p < n$.

The certainty, $\Delta_C$, defined as the distance between the highest and second highest correlation needed to surpass a threshold value, $\beta$, which was set to 0.15. Please note, that for some participants, $\beta$ was adjusted during the familiarisation run to avoid misclassification.

BCI outputs were only produced if $\Delta_C > \beta$. In this case, the data buffer $Y$ was cleared, and a gaze shifting phase of two seconds followed. During the gaze shifting phase the data collection and visual stimulation paused and the user could shift his/her gaze to another target.

The minimum window length and the gaze shifting period are limiting the highest achievable information transfer rate of the used BCI speller. Since the time window length was adjusted individually to optimize performance, the highest possible ITTs also differ individually. The shortest time window used in this experiment was 0.3 seconds only; this value—combined with gaze shifting time of two seconds—results in a minimum spelling time of 108.4 second with the maximum achievable ITR of 53.14 bit/min.

2.6.2. SSmVEP

2.6.2.1. Stimulus design
The pattern of the steady-state motion/movement visual evoked potential (SSmVEP)-based stimulus presentation, was realised using a continuously vertically decreasing/increasing motion of the stimulus target. A thin white frame surrounded the stimuli outlining their maximal size. Each target changed its vertical size in accordance with the function $\cos(2\pi fi/r)$ of the stimulus frequency $f$, where $i$ is the frame index and $r$ is the monitor refresh rate. This function was used to calculate the length of the vertical axis of the stimulus, which was updated after every frame, see figures 3. Figure 4 shows the GUI with the four targets corresponding to the frequencies 8 Hz, 10 Hz, 12 Hz and 15 Hz, used in this study. This smoothly moving pattern creates the illusion of a continuous coin flip around the horizontal axis.

Interestingly, this stimulus is not only generating the full cycle frequency, but also the half-cycle frequency seen as one part of the full motion (shrinking or growing), which would be the 2nd harmonics of the base frequency.
2.6.2.2. Classification

For the SSmVEP paradigm, CCA-based classification with cosine- and sine reference templates was used [49].

For each stimulation frequency, \( f_1, \ldots, f_K \), the corresponding reference signals \( X_k, k = 1, \ldots, K \) were defined as

\[
X_k = \begin{bmatrix}
\sin(2\pi f_1 t) \\
\cos(2\pi f_1 t) \\
\vdots \\
\sin(2\pi N_h f_k t) \\
\cos(2\pi N_h f_k t)
\end{bmatrix}, \quad t = \frac{1}{F}, \frac{2}{F}, \ldots, \frac{n_y}{F},
\]

where \( n_y \) denotes the number of samples considered for classification and \( N_h \) denotes the number of considered harmonics, here \( N_h = 4 \).

The recorded signal \( Y \in \mathbb{R}^{m \times n_y} \) (of the \( m = 16 \) electrodes) was then compared to each of the reference signals \( R_k \) using the CCA. To this end, \( Y \) and \( X_k \) were inserted into (2), yielding \( \rho_i, i = 1, \ldots, K \).

The classifier output label was determined as

\[
C = \arg \max_{k=1,\ldots,K} \rho_k.
\]

As described for the fVEP paradigm, a sliding window mechanism was used, i.e. \( n_y \) was extended and no output was produced, if the threshold criterion was not met.

2.6.3. cVEP

2.6.3.1. Stimulus design

The stimulus design for the cVEP paradigm was realised with m-sequences which are typically used in BCI research because of their autocorrelation property [14]. In this study, four circularly shifted 63-bit m-sequences \( c_i, i = 1, \ldots, K \) were used: The initial code \( c_1 \) was set to \( c_1 = 10101101111011010011100010111100101-0001100001000011111110 \), \( c_2 \) was shifted 8 bits to the left, \( c_3 \) was shifted 16 bits to the left and \( c_4 \) was shifted 24 bits to the left.

The flickering pattern was achieved by alternating the colour of the targets between the binary states ‘black’ (the background colour, represented by ‘0’) and ‘white’ (represented by ‘1’). In this study, the update rate was set to 60 Hz (a quarter of the monitor refresh rate), i.e., every fourth frame, the target colour was updated according to the corresponding code. The duration of one stimulus cycle is dependent on the update rate and the code length, here \( 63/60 = 1.05 \) s. Figure 5 shows the employed sequence.

2.6.3.2. Classification

Template generation, spatial filter generation, synchronisation, target identification and time window mechanism were implemented analogously to the fVEP stimulus paradigm. The only difference to the fVEP paradigm was the different cycle length (1.05 s instead of 1 s). Each trial of the recording session was
stored in a $m \times n$ matrix, where the number of samples was $n = 1.05 \cdot F_s \cdot 3 = 1890$, and the number of electrode channels was $m = 16$.

3. Results

Using the fVEP speller, 83 users were able to successfully finish the copy spelling tasks (i.e. spell the words correctly, using the correction possibilities ‘Back’ or ‘Delete’, if necessary), while for the SSmVEP speller only 80 users from the total 86 were able to complete the tasks (i.e. for the fVEP and the SSmVEP, three and six subjects, respectively, were unable to finish the copy spelling tasks and the trial had to be stopped). The copy spelling tasks with cVEP modality were successfully completed by all 86 subjects of this study.

To test the efficiency of the three paradigms, they were compared with respect performance and the subjective answers to the questionnaires. The subjects who could not use all three spellers were excluded from the statistical analysis of the performance to avoid bias.

3.1. Performance results

For the evaluation of BCI performance, the three copy spelling tasks’ results were averaged. Performance can be evaluated by the spelling accuracy and Information Transfer Rate ( soln). This modified the above mentioned averages slightly: The average (SD) accuracy and ITR for the fVEP paradigm became 95.28 (5.18)% and 31.87 (9.83) bit/min. For the SSmVEP paradigm they became 91.10 (6.01)% and 26.44 (8.04) bit/min, and 97.83 (3.37)% and 40.23 (7.63) bit/min for the cVEP paradigm. The ANOVA and the following pairwise comparisons showed significant differences in ITR between all three VEP paradigms. The respective $p$ values: < 0.001 for fVEP-cVEP, < 0.001 for fVEP-SSmVEP and < 0.001 for cVEP-SSmVEP. The fastest was cVEP, followed by fVEP, and finally SSmVEP.

The accuracies were similarly investigated and all respective $p$ values for the pairwise comparison were < 0.001. The most accurate was cVEP, followed by fVEP, and finally SSmVEP, likewise with the ITR. The accuracy and ITR results of all subjects are shown in figure 6.

The supplementary videos available online at stacks.iop.org/BPEX/6/035034/mmedia Subject_28_fVEP_BCI, Subject_23_fVEP_BRAIN, and Subject_59_fVEP_POWERFUL, display the performance of the fVEP scenario with the spelling tasks BCI, BRAIN and POWERFUL, respectively. The SSmVEP performance is presented on the supplementary videos: Subject_10_SSmVEP_BCI and Subject_14_SSmVEP_POWERFUL, for the spelling tasks BCI, BRAIN and POWERFUL, respectively. The SSmVEP paradigm is shown in figure 7.

By grouping the users according to BCI experience, and investigating the accuracy and ITR of the three paradigms, the results are similar. All differences are significant, except for the group of users with BCI experience between fVEP and SSmVEP regarding both, accuracy ($p = 0.117$) and ITR ($p = 0.107$). This translates to no significant performance differences for experienced users between fVEP and SSmVEP. The means are shown in figure 7.

In addition to comparing the paradigms, gender differences were investigated as well. The accuracy and ITR for the three paradigms were averaged for each participant who could successfully use all three...
paradigms. The average values of female and male participants were compared with a t-test. Contrary to our prior expectations and observations that women can reach better performance\cite{25, 26}, the statistical results showed no significant difference between the two groups. The effects of handedness, vision correction and BCI experience were also checked. The p values of all these statistical comparisons are shown in Table 2. The only significant difference occurred regarding BCI experience in the accuracy and the ITR with the fVEP paradigm. With the fVEP paradigm the mean (SD) accuracy for experienced users was 93.58 (6.36) %, while for naive users it was 96.73 (3.35) %. The mean (SD) ITR was 29.21 (9.91) bit/min for experienced users and 34.14 (9.27) bit/min for naive users using the fVEP paradigm.

### 3.2. Questionnaire results

The answers to the questionnaires were investigated with Friedman tests, while pairwise comparisons were done with Wilcoxon signed-rank tests.

Figure 8 shows the questionnaire results related to the visual stimuli of fVEP, SSmVEP, and cVEP. This was evaluated using the two questions answered before the spelling phases, ‘Comfortable’ and ‘Relaxed’. Statistical comparisons revealed that neither question resulted in significant differences between the paradigms, the results of the Friedman tests were for ‘Comfortable’ $p = 0.263$, while for ‘Relaxed’ $p = 0.078$. The visual stimulation had a higher average score for fVEP and cVEP than for SSmVEP, but not significantly higher. The average and SD values can be found in Table 3.

### Table 2. The results ($p$ values) of statistical comparisons regarding demographic parameters. For all categories except vision correction we used t-tests, for vision correction we used one-factor ANOVA (since there were three possible answers). As an example, handedness SSmVEP in the column ITR notes the p value of a t-test on ITR results with SSmVEP between the left-handed and the right-handed users.

|                          | Accuracy | ITR  |
|--------------------------|----------|------|
| **BCI Experience**       |          |      |
| fVEP                     | 0.010    | 0.027|
| SSmVEP                   | 0.728    | 0.769|
| cVEP                     | 0.161    | 0.163|
| **Handedness**           |          |      |
| fVEP                     | 0.222    | 0.264|
| SSmVEP                   | 0.286    | 0.108|
| cVEP                     | 0.665    | 0.758|
| **Vision correction**    |          |      |
| fVEP                     | 0.631    | 0.319|
| SSmVEP                   | 0.443    | 0.108|
| cVEP                     | 0.178    | 0.075|
| **Gender**               |          |      |
| fVEP                     | 0.966    | 0.430|
| SSmVEP                   | 0.325    | 0.295|
| cVEP                     | 0.232    | 0.314|

Our expectations that SSmVEP is the most comfortable, followed by fVEP and finally cVEP were disproved. Since we did not find any significant difference

![Figure 6. Overall performance averaged for all three spelled words 'BCI', 'BRAIN', and 'POWERFUL' for all VEP paradigms. The horizontal lines note the calculated overall average accuracy and ITR, and include only the subjects who were able to complete all three spelling tasks for a given speller. All 86 subjects were able to complete all the required spelling tasks using the cVEP speller.](image)

![Figure 7. Comparison of the accuracy (left) and ITR (right) of the three paradigms for BCI experienced and BCI naive users.](image)
with this number of subjects, it is likely that there is no difference in the level of comfort of the three paradigms for the majority of people.

All further questions were answered after the spelling tasks, thus they can be influenced by the performance of the spelling. If a paradigm was working fast it may receive more positive answers, however, if a paradigm was not working, it could influence the subjective answers in a negative way. For this reason we analysed the results twice, and for the second analysis we excluded people who could not finish all spelling tasks with all paradigms (eight people were excluded in the total).

Figure 9 shows the results for different parameters of user experience, 'Efficient', 'Clear', 'Supportive', 'Exciting', 'Inventive', 'Enjoyable', and 'Fast'. The statistical analysis found significant differences in all cases and all pairwise comparisons (all \( p < 0.05 \), except between the fVEP and SSmVEP regarding inventiveness (\( p = 0.70 \)). In all of these cases cVEP received the lowest mean, which is the most positive subjective evaluation. The second best was always fVEP, followed by SSmVEP.

After excluding subjects who could not finish all spelling tasks with all paradigms, 78 subjects remained and we recalculated the statistical results. Again all results showed significant differences, except three cases: fVEP compared to SSmVEP - 'Fast' (\( p = 0.12 \), fVEP compared to cVEP - 'Exciting' (\( p = 0.07 \) and fVEP compared to SSmVEP - 'Inventive' (\( p = 0.98 \). The means, other than these three cases, are the same as before, with the cVEP always given the best score.

4. Discussion

One of important findings covered by this study is the question of BCI illiteracy, still broadly used by the BCI community. The originally introduced values of 15%–30% of the whole population to be expected to be BCI illiterates probably mostly holds true only for BCIs based on motor imagery. But, as this issue was never properly discussed by recent publications, many new researchers in the BCI field may erroneously assume that these values are also true for other BCI paradigms, e.g. with regard to the BCIs based on VEPs. As this study was carried out on three different modern visually evoked BCI paradigms only, absolutely no statements regarding the BCI illiteracy rates of other BCI paradigms can be made. Therefore, it is very probable that the issue of BCI illiteracy remains true for non-VEP based paradigms. In addition to that, VEP-based BCIs are also not the best choice for patients who may have limited vision or restricted eye movements.

The study compared three different VEP flickering paradigms, fVEP, SSmVEP, and cVEP, in terms of user-friendliness, BCI literacy rate and overall performance. Our aim during this study was to explore the BCI illiteracy phenomena in more depth, through utilising different VEP-based BCI spellers. The reason behind choosing these spelling paradigms was because of their consistent performance achieved during our previous studies. The goal was to examine whether a user who was labelled as illiterate in one paradigm, could still have a good performance when experiencing another speller. As the results presented, despite the fact that some individuals were not able to finish their spelling tasks using one (or both) of the other spellers, all participants were able to use the cVEP speller; thus, agreeing with the hypothesis.

The users’ subjective opinion was also evaluated using questionnaires to compare the three spellers. Two of the questions were presented to the users after the training phase (i.e. before the spelling tasks of a paradigm). These questions were to assess the level of comfort of the visual stimulation technique. The participants were asked before the spelling task to avoid any performance biases. From previous experience, users tend to see an annoying visual stimulation more comfortable if the spelling task was easy to perform. Hence, the results of the questions shown in figure 8 were the
Table 3. Average (SD) results of the questionnaire ratings regarding the visual stimulation, asked before the main task, and regarding the BCI system, asked after the spelling task.

| Visual stimulation | Comfortable | Relaxed | Efficient | Clear | Supportive | Exciting | Inventive | Enjoyable | Fast |
|-------------------|-------------|---------|-----------|-------|------------|----------|-----------|-----------|------|
| fVEP              | 2.81 (1.60) | 2.68 (1.38) | 2.18 (1.19) | 1.86 (0.98) | 2.06 (1.15) | 2.26 (1.38) | 2.05 (1.27) | 2.56 (1.43) | 2.50 (1.55) |
| SSmVEP            | 3.23 (1.53) | 3.24 (1.45) | 2.92 (1.53) | 2.15 (1.32) | 2.49 (1.37) | 2.67 (1.57) | 2.09 (1.20) | 3.08 (1.84) | 2.77 (1.56) |
| cVEP              | 2.82 (1.44) | 2.86 (1.40) | 1.72 (0.91) | 1.54 (0.89) | 1.77 (0.82) | 2.05 (1.26) | 1.77 (1.12) | 2.15 (1.15) | 1.67 (0.96) |
assessment of the users before they tried spelling using a specific paradigm.

In a previous study, we compared fVEP and cVEP with an 8-target interface [18]; while cVEP yielded slightly better accuracies in the off-line analysis, participants tended to prefer the more subtle stimulation of the SSVEP paradigm. In general, a major issue in VEP-based BCIs is the rapid flashing, which is perceived as annoying by many users. To address this problem, we included SSVEP paradigm in this study, which can yield a much more subtle visual stimulation, according to the literature [21, 22]. However, on the basis of the questionnaire results, participants tended to prefer the flickering of the fVEP or cVEP. The movement pattern of the SSVEP stimulation (flipping coin motion) might not yield high ITR; but different patterns (e.g. pulsating movements) may be a better option in terms of user friendliness. In a future study, several flickering patterns should be compared.

The second set of questions was aimed to assess the general experience of a spellers system. The results in general mirror the performance results, which likely had a big impact on these scores. These subjective results show that cVEP is the best method in regards to both—performance and user evaluation. Because it was the fastest and caused less discomfort than the other two tested paradigms, its use in future experiments is well founded.

The accuracies and the ITRs results were compared across the demographics of the participants. There was no significant difference in the performance between male and female. This contradicts some results in the literature, including the trends from the previous papers [25, 26]. However, even though there was no correlation between the age and the performance, the age range of the participants was relatively narrow; mainly focused around the typical ages of university students, with some minor exceptions.

To optimise performance, state-of-the-art hardware and software setup were utilised. Regarding the signal acquisition, several studies reported that the number of signal electrodes correlates with BCI performance [43, 50, 51]. For this reason, to reduce BCI illiteracy, a comparably high number of EEG signal electrodes (16) was employed. Regarding the signal classification algorithms, well established ensemble-based classification methods and CCA-based spatial
filters were used, which achieved high ITRs and accuracies in previous studies [17, 18, 52].

It should be noted, that besides the three paradigms compared in the presented study, other VEP paradigms have been investigated in the literature during recent years. For example, the transient VEPs (tVEPs) and the motion-onset VEPs (mVEPs) were not included in this study, as the achievable ITRs are much lower in comparison (see, e.g., [13]).

Only short spelling tasks were performed, as the participants needed to go through the training with all three paradigms and the total duration of the experiment was kept to a maximum of two hours. Over half of the participants were BCI naïve as it is shown in table 1. Additional familiarization could lead to overall higher accuracies.

As it has been intensively discussed in BCI literature, a major difficulty in VEP-based BCI research lies in finding an optimal solution, balancing accuracy and speed. In asynchronous applications, like the presented three-step spelling application [42], commands require probabilities of the different frequency stimuli to exceed their corresponding thresholds, otherwise the classifier output is rejected. The careful calibration of these thresholds balances system speed and system accuracy.

In previous SSVEP studies, the BCI literacy rate was steadily improved. While Volosyak et al [41] reported a BCI illiteracy rate of 14%, with some modifications this was reduced to 2.33% in two years’ time [26]. Guger et al [24] demonstrated that their SSVEP-based BCI could enable effective communication for every one of their 53 subjects. A possible cause for high literacy rates is the low number of stimuli. Guger et al [24] and Volosyak et al [26] both employed BCIs with only four stimuli. In addition, Guger et al [24] used a relatively longer classification time window, which also helped to reach a BCI literacy rate of 100%.

The focus of this study was put on high BCI literacy rather than speed. For this reason, a low number of classes was used. Research focusing on maximising the ITR usually employs a much higher number of targets (typically 32 targets for cVEP and 40 for fVEP and SSmVEP, respectively). High mean ITRs of 144 bpm for cVEP [17], 91.2 bpm for SSmVEP [22], and approx. 267 bpm for fVEP [4] have been achieved. However, Spüler et al [17] reported illiteracy due to excessive blinking in one case. In previous studies with multi-target SSVEP systems we found that the higher the number of targets is usually connected to the higher the BCI illiteracy rate [25, 26]. Modern implementations of cVEP allows even much higher information transfer rates, on average of 175 bpm and up to 1237 bpm for the best subject [53]. We would like to investigate the impact of the number of targets on cVEP performance in a future study.

It should be pointed out, that this study was conducted with healthy young adults, as they were recruited from the university students. In previous studies, we found that age affects BCI performance [42, 54]. For this reason they do not reflect the general population. Moreover, potential end users tend to have lower BCI performance. Further tests with disabled participants are planned.

The presented results are valuable, as the reduction of BCI illiteracy is of crucial importance with respect to commercial exploitation. Until now this unsolved problem of the BCI illiteracy was one of the major limiting factors preventing the commercial exploitation of BCIs. This seems to be solved now, at least for the VEP-based BCIs.

In summary, the study demonstrates that reliable BCI control can be achieved by a broad population. The presented system yielded a 100% literacy rate and high accuracies due to the following non-exhaustive list of conditions: (1) frequencies, time windows, and thresholds were calibrated individually for each user, (2) long classification time windows were used for poor performers, (3) the number of stimulation frequencies was only four, (4) the participants represent the group of young and healthy students and do not reflect the general population.

5. Conclusion

In this study, we intended to investigate the question of estimated rate of BCI illiteracy for VEP-based BCIs and provide an adequate update of this value. During this study, the performance of three different BCI VEP-speller systems, fVEP, SSmVEP, and cVEP, was compared across a relatively large number of users. The results show that all 86 users of this study were able to perform BCI operation with at least one VEP paradigm. Best results were achieved with the code-modulated visual evoked potentials (cVEP), where all 86 subjects were able to use the BCI spelling application with the average accuracy of 97.83% and a mean information transfer rate of 40.23 bit/min, respectively. Slightly inferior results were achieved with the fVEP speller, where 83 subjects were able to successfully finish all spelling tasks with a mean accuracy of 95.28% and an information transfer rate of 31.87 bit/min, respectively. Finally, 80 out of 86 subjects were able to successfully finish all spelling tasks using SSmVEP paradigm, with a mean accuracy of 91.10% and an averaged information transfer rate of 26.44 bit/min.

These results show that it is possible that the whole population can achieve a BCI operation with modern VEP-based BCIs. Moreover, as these results show accuracy and ITR levels similar to those of other recently published studies, it is necessary to update the previously published BCI illiteracy rates for the brain-computer interfaces based on modern paradigms utilising visual evoked potentials.

Another result worth mentioning is the fact that the demographic parameters, as well as handedness,
vision correction, BCI experience, etc., have no significant effect on the performance of VEP-based BCIs.

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