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Stimulus Paradigm for an Asynchronous Concurrent SSVEP and EOG Based BCI Speller System

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ABSTRACT The brain computer interface (BCI) speller system can be classified into synchronous and asynchronous type. In synchronous type, one of the target characters is selected with specific interval periodically even if the user is making or not making attention on the target, whereas, in asynchronous case, the target character will not be selected until a confirmation signal is received from the user. In this proposed study a novel oddball stimulus paradigm is introduced on the hybrid steady state visual evoked potential (SSVEP) and electrooculogram (EOG) speller system to achieve an asynchronous control and high performance. The proposed system consists of forty characters grouped and indexed into five flickering unique frequency visual stimuli. Each visual stimulus is assigned with eight unique characters. The characters in each group are randomly highlighted by the oddball paradigm and the user performs blink eye movement in synchrony with the desired target character highlight. An asynchronous control is achieved by EOG signal and oddball paradigm because the target character will not be selected until the user performs blink eye movement. The stimulus paradigm helps the user to select the target group and desired target character, concurrently by SSVEP and EOG signal which increases the performance of the system. The proposed asynchronous speller system is tested and validated on ten subjects. The online classification accuracy and information transfer rate (ITR) of the proposed hybrid speller system are 99.38% and 116.58 bits/min respectively. Performance metrics of the proposed system are compared with the conventional speller systems and is found to be much superior to existing systems.

INDEX TERMS Steady state visual evoked potential (SSVEP), brain computer interface (BCI), asynchronous speller, electrooculogram (EOG).

I. INTRODUCTION

Researchers have been developing various types of brain computer interface (BCI) based keyboard/speller systems to help needy individuals for the past few decades. BCI technology provides a communication pathway directly from the human brain to the external world without using any normal peripheral pathways of the brain (speech, handwriting, hand movement, etc.) [1], [2]. It directly controls the external environment by electroencephalogram (EEG) signal components like, event related synchronization/desynchronization (motor imagery signals), steady state visual evoked potential (SSVEP), slow cortical potential and P300 [3]–[5]. Among various BCI applications including communications and controlling external devices, BCI speller is still one of the most important applications studied in most researches. SSVEP-based BCI spellers have the advantage of greater information transfer rate (ITR), higher signal-to-noise ratio, fewer EEG channels and less training time, compared to other BCI control signals/modalities. Hierarchical structures have been widely used in SSVEP-based spellers. Although these structures have desired accuracy, the ITR requires to

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be improved. Applying phase information into frequency coding in SSVEP visual stimuli design has also achieved desirable performance [6], [7]. However, phase detection requires training data, since subject variability is high in phase. Recognizing the phase information requires large amounts of computation which is time-consuming in online applications. To achieve desirable recognition accuracy and high ITR, the hybrid brain-computer interface (HBCI) spellers are used.

In HBCI system, a BCI control signal is combined with another BCI control signal or with a human machine interface (HMI) bio signal (example: electrooculogram (EOG), electromyogram (EMG) etc.,) in a sequential or simultaneous combination. In sequential HBCI, the modalities act as time-sharing. In other words, the first modality selects the target among several options and the second one performs the process on the selected target [8], [9]. The sequential combination has a significant effect on reducing errors by dividing a complex task into several stages [10]. The time duration for detecting a single target is higher in sequential combination. In simultaneous HBCI, the BCI/HMI modalities work concurrently with each other [11], [12]. The control signal in each modality acquired and processed in the same time window. Therefore, the target detection time is very less as compared to the sequential combination. The ITR of the speller/keyboard system depends on classification accuracy, target detection time and number of target characters. In hybrid system the number of target characters is increased by the combination of two or more control signals and the classification accuracy is increased by divide and conquer method. The target detection time is the drawback in some of the sequential hybrid speller system, which is addressed by the simultaneous HBCI system. Therefore, the simultaneous hybrid BCI system gives good performance metrics like, high classification accuracy, high ITR and less target detection time [13].

Electrooculogram is a biological signal used in HBCI/HMI systems [14]. It is generated by an electrical dipole with a positively charged cornea and the negatively charged retina, which measures the voltage changes caused by eye movement. The resulted electrical signal can be recorded using pairs of electrodes around the eyes [15]. This signal shows unique pattern for each eye movement (up, down, left, right, gaze, blink and wink) which can convey highly recognizable information from the user's intention [16]. The EOG-based HMI systems are an advantageous technology since most paralyzed people can move their eyes. Eye movements are an optional and comfortable activity of users [14]. They do not require much training and works very fast. Fewer channels are also required in these systems. The kind of eye movement is easily recognized in the temporal domain without the need of preprocessing. Hence, they do not require complicated signal processing approaches. Therefore, the EOG signal is used in several applications [17]–[19].

The combination of SSVEP-EOG and P300-EOG based hybrid keyboard/speller systems are largely investigated by many researchers for real life applications [8], [16], [20]–[22]. The P300 based HBCI systems are time-consuming which requires collecting a lot of trials until the classification output is desirable which decreases the ITR [11], [23], [24]. Most of the developed HBCI speller systems are sequential type. The sequential HBCI modality has a significant effect on reducing the error, but it increases the target selection time which leads to less ITR [13]. The target detection time is less in the simultaneous HBCI system because control signals are used concurrently.

Most of the developed hybrid EEG-EOG systems are synchronous in nature and it does not suit well for practical usage because, the user should perform the task within a specified time window for target selection. If the task is not performed within a specified duration, it will lead to error or misclassification [25]. The users need to follow the instructions provided by the speller system and they cannot take rest while performing the task. The controlled environment demands more mental workload, which leads to discomfort and fatigue to the users. In an asynchronous system the users can have a complete control on the system. There is no specified time duration for selecting a target. The target will not be selected by the system until the control signal is generated by the users. The users could take a rest while performing the task by changing the system mode from active to idle state [23], [26]–[28].

The practical BCI speller system needs an asynchronous control, more target characters, high accuracy and high ITR for providing better communication. In order to address all the above-mentioned points, a novel oddball stimulus paradigm with simultaneous combination of SSVEP and EOG based hybrid BCI system is proposed in this study.

The P300 based speller systems are using an oddball paradigm for eliciting/evoking the P300 response [23], [27], [29]. The oddball paradigm randomly highlights the target characters and user has to perform mental tasks in synchrony with the desired target character highlight for evoking P300 component in EEG signal. The P300 based speller system needs minimum 4 to 5 complete rounds of highlights for detecting the P300 component and target character, which increases target detection time.

In this proposed study, an oddball paradigm is used with eye movement signal. The user has to perform blink eye movement when the desired target character is highlighted by an oddball paradigm. An eye movement occurs quickly and a blink eye movement is detectable at short time window length (approximately 300 ms), which decreases the target detection time.

Most of the conventional SSVEP based speller systems are having tradeoff between the classification accuracy and the number of targets. In order to increase the number of commands, classification accuracy and ITR in the proposed speller, the oddball paradigm has been used in an effective way by applying a simultaneous combination of EOG with SSVEP component. As compared to other EEG components SSVEP is detectable at short window length and EOG is also detectable at a shorter time, therefore a simultaneous combination of SSVEP and EOG increases ITR of the speller system.

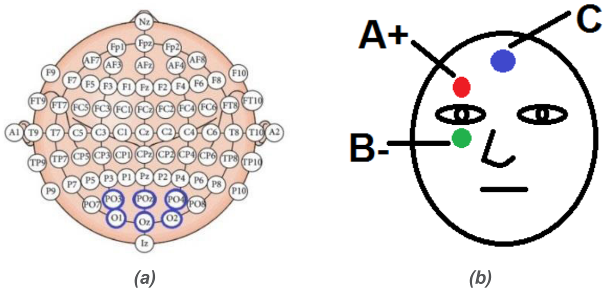
In this proposed speller layout, the target characters are arranged in the form of groups, the target group is selected by SSVEP and an individual target is identified from the EOG signal (explained in detail in section II B and C). The proposed hybrid speller uses five unique well separated frequencies for visual stimulus design for eliciting the SSVEP response. The oddball paradigm increases the number of targets in the speller layout, though only five SSVEP visual stimuli were used. The proposed system uses SSVEP and eye blink signals for target selection. The subject has to perform blink eye movements in synchrony with the oddball paradigm for desired target selection. The desired target will not be selected by the system until a blink eye movement has been performed by the user. The proposed system has achieved an asynchronous control by the EOG modality (blink eye movement and oddball paradigm). The SNR of the SSVEP signal gets increased by the oddball paradigm, because the user has to give more attention on the paradigm for selecting the desired target. A simple and convenient asynchronous SSVEP-EOG based simultaneous HBCI system has been presented in this study.

The rest of the paper is organized as Materials and Methods, Experiments and Results, Discussions and Conclusion. The subject's information and details of EEG and EOG data acquisition, speller design, experimental setup and paradigm are explained in Materials and Methods section. The EOG feature extraction and detection, SSVEP response time analysis, the experimental procedure and results of synchronous and asynchronous systems are analyzed and presented in Experiments and Results and Discussion sections respectively. The summary of the proposed study is presented and concluded in the Conclusion section.

II. MATERIALS AND METHODS

A. SUBJECTS INFORMATION AND DATA ACQUISITION

Ten healthy individuals (8 males and 2 females with a mean age of 27.4 years) volunteered to participate in the proposed SSVEP-EOG system validation/tests. All individuals had normal or corrected to normal vision. The aim of the experiment was explained to each subject and they signed the informed consent approved by our ethical committee (IITM ethical committee, IIT Madras, India). EEG and EOG signals were recorded simultaneously by using BioDaq v01 data acquisition system (open BCI data acquisition board) [30]. During the experiment, the subjects were seated on a chair which had 60 cm distance from the screen. In accordance with the International Society for Clinical Electrophysiology of Vision (ISCEV) standard for visual evoked potential, the SSVEP response is strong in the occipital area which is very close to the primary visual cortex. Therefore, EEG electrode sites O1, O2, Oz, PO3, PO4 and POz have been chosen and the reference electrode was placed on the right/left mastoid bone, shown in Figure 1.a.



(a) (b)

FIGURE 1. **(a) EEG, (b) EOG electrode placement.**

The EEG data were collected by using sintered Ag/AgCl electrodes. The electrode locations of an EOG recording are shown in Figure 1.b. For recording corneal-retinal potential surface Ag/AgCl electrodes (A-positive and B-negative) were placed on the above and below (vertical axes) of the left/right eye shown in Figure 1.b. The electrode C is connected to ground. The EOG and EEG data were recorded with bipolar and unipolar electrode configurations at the rate of 250 Hz per channel. The 50 Hz notch filter and bandpass filter (0.1 to 40 Hz for EEG and 0.1 to 30 Hz for EOG) were applied on the acquired data in order to remove the powerline interferences and noises.

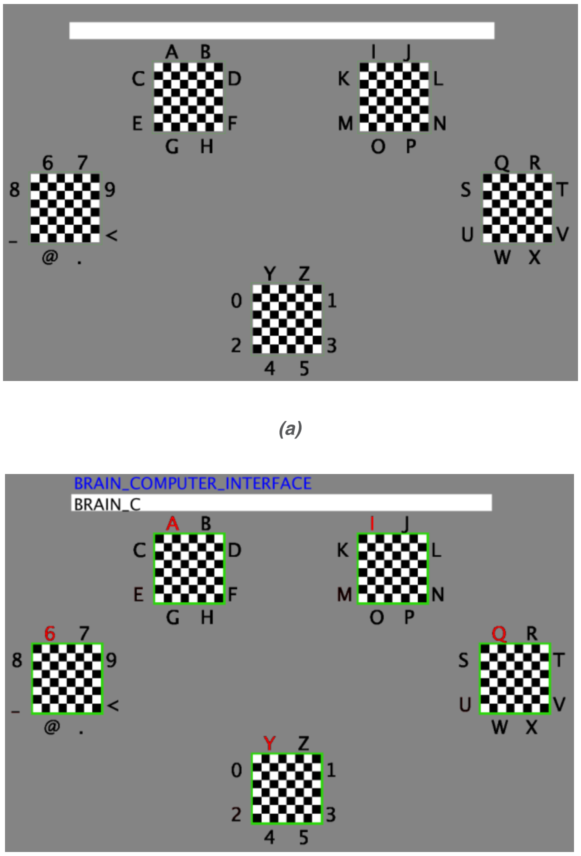
B. GRAPHICAL USER INTERFACE AND STIMULUS DESIGN

The proposed keyboard system consists of forty targets which include alphabets, special characters and numbers shown in Figure 2. The target characters and visual stimuli are displayed to the subjects using a 60 Hz refresh rate LCD monitor. The forty targets are equally divided into five groups and each group has eight target characters. Five square checker board (8 × 8 pattern) visual stimuli are designed using five unique frequencies (10, 8.57, 7.5 6.667 and 6 Hz) and each target group is assigned to a unique visual stimuli shown in Figure 2. The selected frequencies are the integer division of monitor refresh rate (60 Hz). The target characters are arranged on the sides of the square checker board stimulus (each side two target characters) shown in Figure 2. A Processing (Java) software platform has used for designing the keyboard layout (graphical user interface), visual stimuli, data acquisition and processing.

C. EXPERIMENTAL SETUP AND PARADIGM

The experimental setup of a proposed hybrid speller system shown in Figure 3. It consists of data acquisition unit (electrodes and BioDaq v01), personal computer and an extended monitor for displaying the targets. The distance between the subject and extended monitor is maintained at 60 cm considering the minimum visual angle between two adjacent stimulus is 2 degrees to avoid overlapping.

The target selection in this proposed study consists of two steps, 1) target group selection by SSVEP and 2) individual target selection by EOG (blink eye movement). The target group and individual target are selected within the same time



(a)

(b)

FIGURE 2. **(a) Speller layout, (b) Proposed paradigm.**

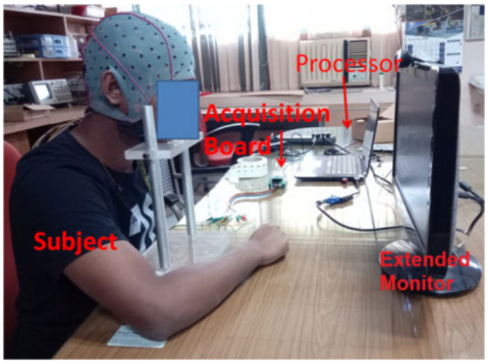


FIGURE 3. **Experimental setup.**

window/period by using the simultaneous combination of SSVEP and EOG.

Initially the speller will be in idle condition showing the target characters in black color and the visual stimuli will be flickering at a designed frequencies as shown in Figure 2.a. The speller is initiated/activated by triple eye blink. Once the triple eye blink is detected, the speller layout is changed into active condition by changing/turning the outer border of all the stimuli into green color as shown in Figure 2.b.

Once color of the stimuli edges/borders turns into green, the experimental paradigm (oddball paradigm) starts by highlighting the target characters in red color simultaneously one by one from all groups shown in Figure 2.b and each character is highlighted in red color for 300 ms. In a single sequence, the oddball paradigm randomly highlights all target characters once with red color. The paradigm needs 2.4 second time duration for completing the one full round (one sequence) of the highlights (8-times × 300 ms = 2.4 second). On turning the edges of the visual stimuli into green color, the subjects are instructed to concentrate on the desired target visual stimulus (target group selection). The subjects should perform an eye blink movement in synchrony with the desired target character highlight (red color) for target selection. The SSVEP signal is used to identify the desired target group and the onset of eye blink time is used for selecting desired target character from the selected group. In this proposed study, the SSVEP and eye movement signals are collected simultaneously in a single time window. If, no eye movement is detected after completing a single sequence, the paradigm again starts highlighting the target characters randomly (next sequence). In this way the paradigm continues the random highlighting. If subjects are not performing any eye movement until five rounds (five sequence) of the highlights, then the system mode will be shifted/changed into idle. The mode of the speller will shift/change again into active mode, if the system detects triple eye blink. The asynchronous control is achieved by the eye blink signal. Unlike conventional synchronous speller system, the proposed system won't select any targets until the eye movement is performed. Errors/typos are avoided by the asynchronous control. The subjects can shift the system mode from active to idle whenever they want a rest while doing the experiment and vice versa.

D. SSVEP FREQUENCY RECOGNITION METHOD

The spatial filtering techniques are used for extracting SSVEP component present inside the EEG data. The SSVEP components are extracted by measuring the relationship or similarity between the acquired multichannel EEG data (X) and reference matrix (Y). In this study, the extended multivariate synchronization index (EMSI) algorithm is adopted for SSVEP frequency recognition [31]. The reference matrix Y consists of sine cosine signals with fundamental frequency and harmonics.

In 2014, Zhang *et al.*, [32] proposed the multivariate synchronization index (MSI) method for recognizing the SSVEP frequency present inside the EEG data. The aim here is to compute the synchronization between two datasets (X and Y), which may be of different dimensionality. The MSI method involves the use of the S-estimator as the index, which is used as a feature for classification. In 2017, Zhang *et al.*, [31] proposed the extended MSI (EMSI) algorithm for increasing the frequency recognition rate in the standard MSI algorithm. They have introduced the first order time delayed version of EEG data (X^{τ}) during the synchronization index calculation and τ is the number of delayed samples. The delayed version of EEG data is treated as an additional channel in X.

III. EXPERIMENTS AND RESULTS

A. EOG FEATURE EXTRACTION AND BLINK DETECTION

In order to find the features for a blink eye movement detection the subjects were asked to perform blink eye movement forty times as per the instruction provided by the experimental paradigm. The experimental paradigm consists of the eye movement window followed by a rest window. The time duration of 1 second was given to each time window. The total time period requires to complete forty blinks is 80 seconds. The subjects have performed blink eye movement during eye movement window and they have instructed to give rest to their eyes during rest window. The single blink eye movement data were collected from each subject. The collected data were indexed and stored by subject number. Three sessions of EOG data were collected from all the subjects and each session contains 40 blinks. Two session data were used for finding the features and one session data were used for testing.

Huang *et al.*, [33] and Ma *et al.*, [16] developed the multi threshold algorithm for blink eye movement detection. The same algorithm is adopted in this proposed study for blink detection. The recorded EOG is first filtered by digital bandpass filter (0.1-30 Hz) and down sampled to 32 Hz [16]. The features are extracted from original filtered EOG data and first order differentiated EOG data. Original and first order differentiated single blink eye movement EOG signal shown in Figure 4. The parabolic fit method was adopted for finding peak and valley from the first order differentiated EOG signal. In this study, maximum value of a filtered EOG data A_{max}, peak value of differentiated EOG data D_{max}, valley value of differentiated EOG data D_{min} and duration D_{pn} are extracted as a feature for eye blink detection as per the studies [16], [33]. The duration D_{pn} is the interval between peak and valley of differentiated EOG data.

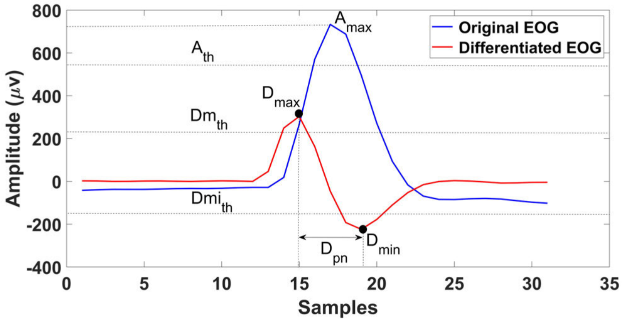


FIGURE 4. Original and first order differentiated EOG signal.

The threshold for amplitude (A_{max}), duration (D_{pn}) and peak (D_{max}) and valley (D_{min}) value of differentiated EOG data were calculated as per the paper [16] by using two sessions of recorded data. The successful detection of a blink eye movement should satisfy the following inequalities:

$$\begin{aligned} A_{max} &\geq A_{th} \\ D1 \leq D_{pn} &\leq D2 \\ D_{max} &\geq Dm_{th} \\ D_{min} &\leq Dmi_{th} \end{aligned} \tag{1}$$

where, A_{th} is the threshold value for amplitude, Dm_{th} and Dmi_{th} are the threshold value for peak and valley of the differentiated EOG data and D1 and D2 represents the minimal and maximal thresholds of the time duration in samples.

The threshold values of all the features are calculated for all individual subjects and validated with one session recorded test data. The classification accuracy of 99.9% was obtained from test data. Basically, two types of error would be expected in the EOG detector. Type 1 error was that the subject moved his/her eye correctly but it was not detected by the EOG detector. Type 2 error occurred when the subject natural moved his/her eyes but the system falsely detected it as the selection. So, involuntary eye movement may be a deficiency of the speller and we can overcome it by determining suitable threshold value. In this study, the Type 2 error was overcome by the threshold value and other features, which is extracted from the differentiated EOG signal.

B. ESTIMATION OF SSVEP DETECTION/RESPONSE TIME (OFFLINE ANALYSIS)

The SSVEP is elicited by the visual stimulus flickering at a designed frequency. The SSVEP response time is subjective, it will not be same for all the subjects. Each subject needs different time period/window for detecting the SSVEP response [34], [35]. The classification accuracy of the speller system mainly depends on the SSVEP detection time window. Therefore, 10 sessions of offline experiment were performed on all the subjects for finding the optimal SSVEP stimulation/detection time window for all the individual subjects.

The GUI of offline experiment consists of five visual stimuli flickering at 6, 6.667, 7.5, 8.57 and 10 Hz shown in Figure 5. The experiment is started by highlighting the visual stimulus in green color one by one in an order. The subjects were instructed to concentrate on the highlighted visual stimulus one by one as per the visual instruction

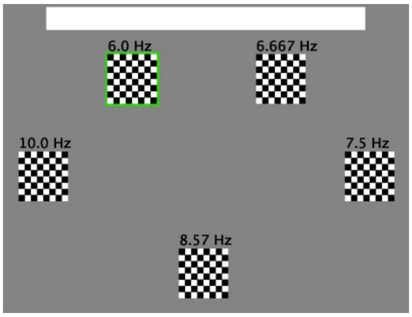


FIGURE 5. SSVEP paradigm (offline).

provided by the system as shown in Figure 5. The green color highlights on the edge/border of the visual stimulus was made to appear up to 5 seconds. This highlighted time duration is called SSVEP stimulation time period. The buffer time of 0.5 seconds was given to all the subjects as a rest period at the end of the SSVEP stimulation period/window. The green color highlight on the border of the visual stimulus was made to disappear during the rest time period. The offline experimental paradigm consists of a sequential combination of the SSVEP stimulation time window and rest time window. All the visual stimulus were highlighted one time in a single session.

To find the optimal SSVEP stimulation/detection time window for an online system, the stored EEG data were analyzed at different time lengths (1.5, 2, 2.5 and 3 seconds). The different time length data were taken from the onset of the SSVEP stimulation time window. In this study, the extended multivariate synchronization index (EMSI) method was adopted for SSVEP frequency recognition or classification. The EMSI algorithm was applied on all the time segment/ time length data and the corresponding classification accuracy across all the subjects shown in Figure 6. The average classification accuracy of 98.8% was obtained at 2.5 second time window across all the subjects. The optimal time period required for single blink eye movement is 300 ms [26], [36]. The oddball paradigm requires 2.4 s for completing one sequence of highlights (8-times × 300 ms=2.4 s). Therefore, 2.5 second time window was chosen as an optimal SSVEP stimulation time window for online SSVEP classification.

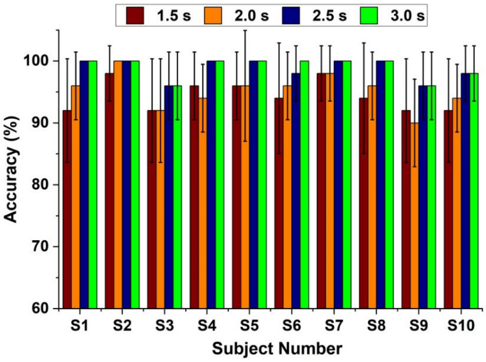


FIGURE 6. Average SSVEP classification accuracy (offline).

C. CUE GUIDED ONLINE SSVEP-EOG SYSTEM (SYNCHRONOUS CASE)

The proposed cue guided speller system works in a synchronous mode. To get accustomed with the proposed system, each subject has instructed to perform 3 practice sessions. The cue guided program randomly selects a target from the keyboard layout and displays on the top of the text window (as shown in Figure 2.b). Subjects were instructed to select the displayed target character. In a single session all the target characters were selected once and displayed above the text window. The experiment was activated/initiated by subject's triple eye blink movement. The green color border on the edge of the visual stimuli indicates the active condition of the speller. The cue guided paradigm randomly pick up the target character and displays above the text window. The oddball paradigm starts to highlight the target character from all the group simultaneously and the subjects were instructed to blink in synchrony with the displayed target character highlight. The characters in the speller layout were highlighted once within the SSVEP stimulus time window. The eye movement detection algorithm was performed at each individual highlights and the EMSI algorithm was performed at the end of the SSVEP stimulus time window. The detected SSVEP frequency value was used for target group selection and the desired target from the selected group was detected by an eye blink signal. A time period of 0.5 seconds was given as a rest period after selecting a single target. The green color borders were made to disappear during the rest period. At the end of rest window, the green color borders were made to appear for next target selection and the subjects were instructed to select the next displayed target character. The same procedure was repeated for the remaining characters as target selection window followed by rest window. If the subjects are not performing any eye movement within a SSVEP stimulus window the corresponding displayed character is classified as an error because the online cue guided experiment working in a synchronous mode. The subject should perform blink eye movement within a SSVEP stimulus window duration.

Three sessions of cue guided online analysis were performed on all the subjects. A time duration of 10 minutes was given as a relaxation period between two consecutive sessions. The information transfer rate and classification accuracy of this experiment were calculated and shown in Table 1 and Figure 7. In synchronous system the target detection time window (time duration of the green color border on the outer edge of the stimuli) is considered for ITR calculation.

TABLE 1. Information transfer rate of cue guided (synchronous) and free spelling (asynchronous) experiments.

Subject number	Single target detection time (in seconds)		ITR (bits/min)	
	Cue guided	Free spelling	Cue guided	Free spelling
S1	2.5	2.9	114.51	107.76
S2	2.5	2.54	122.68	125.71
S3	2.5	3.05	110.79	97.08
S4	2.5	2.85	118.44	109.65
S5	2.5	2.88	116.44	110.87
S6	2.5	2.78	114.51	110.32
S7	2.5	2.67	120.51	119.59
S8	2.5	2.74	116.44	116.54
S9	2.5	2.93	105.49	102.82
S10	2.5	2.66	112.63	117.48
Average	2.5	2.8	115.24	111.78

TABLE 2. Results of sentence spelling/typing experiment (Asynchronous mode.)

Subject number	Target sentences	Single target detection time (in seconds)	Classification accuracy (%)	ITR (bits/min)
S1	BRAIN COMPUTER INTERFACE INDI(I)AN INSTITUTE OF TECHNOLOGY MADRAS	2.69	98.36	127.42
S2	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.58	100	137.92
S3	BRAIN COMP(S)UTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.74	98.36	125.1
S4	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.64	100	134.79
S5	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.59	100	137.39
S6	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.61	100	136.34
S7	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.57	100	138.46
S8	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.8	100	127.09
S9	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECH(3)NOLOGY MADRAS	2.78	98.36	123.3
S10	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.71	100	131.31
Average		2.671	99.5	131.91

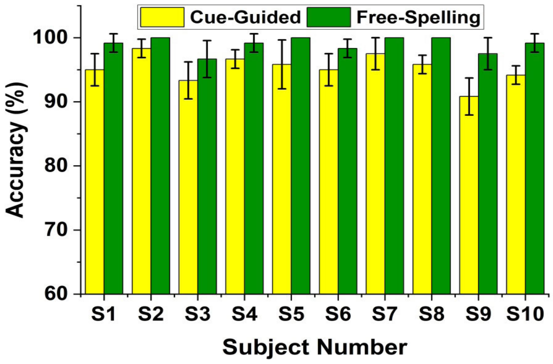


FIGURE 7. Classification accuracy of online cue guided (synchronous) and free spelling (asynchronous) system.

D. ONLINE FREE SPELLING EXPERIMENT (ASYNCHRONOUS CASE)

The experimental procedure of an online free spelling experiment is discussed in section II.C (Almost similar to an online cue guided system). The subjects are free to select any target based on their desires and they are instructed to select all forty targets in a single session. Three sessions of online free spelling task were performed by all subjects. In cue guided online task, the target character is selected at the end of the SSVEP stimulus time window, whereas in free spelling experiment the target will be selected at the end of SSVEP stimulus time window if the subject has performed blink eye movement within SSVEP stimulus time window. If, no eye movement is performed up to the end of the SSVEP stimulus window, the system won't select any target. The green color borders were made to appear up to the eye movement is performed by the subjects because the online free spelling experiment works in an asynchronous mode. Once the eye movement is detected by the multi threshold algorithm the corresponding character is selected and displayed in the text window. In both cue guided and free spelling case the EMSI algorithm recognize the SSVEP frequency at the end of SSVEP stimulus time window (2.5 s). The minimum time period required to detect a single target in asynchronous case is 2.5 seconds and maximum time duration is depending on the subjects, illustrated in Table 1.

A relaxation or rest period of 10 minutes was given to all the subjects between two consecutive sessions. The classification accuracy is calculated by dividing correctly identified targets by total number of targets. The information transfer rate (ITR) and classification accuracy of the online free spelling experiment shown in Table 1 and Figure 7.

E. ONLINE SENTENCE TYPING/SPELLING EXPERIMENT (ASYNCHRONOUS CASE)

In the sentence typing experiment, subjects were instructed to type/spell the given sentences one by one. The subjects have taken their own relaxation time after typing a single sentence. The given sentences are BRAIN COMPUTER INTERFACE and INDIAN INSTITUTE OF TECHNOLOGY MADRAS. In this experiment/task, both synchronous and asynchronous modes/systems were used by all the subjects and a counterbalancing experimental approach was adopted. The results of sentence spelling/typing experiment using the proposed asynchronous speller system are shown in Table 2. In this Table 2, the letters in the bracket indicate error or typos made while typing the given sentences. The spelling accuracy of 100% was obtained for seven subjects and average spelling accuracy across all the subjects is 99.5%. Similarly,

TABLE 3. Results of sentence spelling/typing experiment (Synchronous mode.)

Subject number	Target sentences	Single target detection time (in seconds)	Classification accuracy (%)	ITR (bits/min)
S1	BRAIN CO(N)MPUTER INTERFACE INDI(I)AN INSTITUTE OF TECHNOLOGY MA(L)DRAS	2.5	95.08	128.55
S2	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.5	100	142.34
S3	BRAIN COMP(S)UTER INT(C)ERFACE (J)INDIAN INSTITUTE OF TEC(F)H(K)NOLOGY MADRAS	2.5	91.8	120.85
S4	BRAIN COMPUTER INTERFACE INDIAN INS(S)TITUTE (W)OF TECHNOLOGY MADRAS	2.5	96.72	132.67
S5	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY MADRAS	2.5	100	142.34
S6	B(X)RAIN COMPUTER INTERFAC(B)E INDIAN INSTITU(V)TE OF TECHNOLOGY MADRAS	2.5	95.08	128.55
S7	BRAIN COMPUTER INTERFACE INDIAN INSTITUTE OF TECHNOLOGY M(D)ADRAS	2.5	98.36	137.11
S8	BRAIN COMPUTER INTER(H)FACE INDIAN INSTITUTE OF TECHNOLOG(2)Y MADRAS	2.5	96.72	132.67
S9	BRAIN COM(O)PUT(G)ER INTE(W)RFACE INDIAN INSTITUTE OF TECH(3)NOLOGY MA(H)DRAS	2.5	91.8	120.85
S10	BRAIN COMPUTE(Q)R I(V)NTERFACE INDIAN INSTITUTE OF T(B)ECHNOLOG(0)Y MADRAS	2.5	93.44	124.62
Average		2.5	95.9	131

TABLE 4. Results of sentence spelling/typing experiment (own proverbs/sentences).

Subject number	Chosen sentences	Typed sentences	Single target detection time (in s)	ITR (bits/min)
S1	EARLY BIRD CATCHES THE WORM	EARLY BIRD CATCHES THE WORM	2.71	105.27
S2	CLEANLINESS IS NEXT TO GODLINESS	CLEANLINESS IS NEXT TO GODLINESS	2.64	113.64
S3	PRACTICE MAKES PERFECT	PRACTICE MAKES PERFECT	2.62	102.12
S4	ACTIONS SPEAK LOUDER THAN WORDS	ACTIONS SPEAK LOUDER THAN WORDS	2.66	111.75
S5	BEAUTY IS ONLY SKIN DEEP	BEAUTY IS ONLY SKIN DEEP	2.63	104.6
S6	ALL THAT GLITTERS IS NOT GOLD	ALL T(P)HAT GLITTERS IS NOT GOLD	2.7	99.46
S7	ALWAYS PUT YOUR BEST FOOT FORWARD	ALWAYS PUT YOUR BEST FOOT FORWARD	2.65	114.21
S8	BARKING DOGS SELDOM BITE	BARKING DOGS SELDOM BITE	2.66	103.42
S9	CURIOSITY KILLED THE CAT	CURIOSITY KILLED THE CAT	2.73	100.77
S10	HONESTY IS THE BEST POLICY	HONESTY IS THE BEST POLICY	2.68	105.23
Average			2.668	106.05

the results of sentence spelling experiment using the proposed synchronous speller system are shown in Table 3. The average spelling accuracy of the synchronous system is 95.9%. The information transfer rate of the sentence typing experiments is shown in Table 2 and 3.

The paired t test with bonferroni correction was performed between the classification accuracies of synchronous and asynchronous modes/systems. There is a significant difference between their mean accuracies ($p<0.005$). The average ITR of the synchronous and asynchronous systems are almost similar, the paired t test result shows that there is no significant difference in their mean ITR. Classification accuracy and ITR are the important performance measures of the practical BCI systems. The test result shows that the proposed asynchronous speller system is giving high value for both the performance measures as compared to synchronous system. After typing the given sentences, each subject had chosen their own proverbs/sentences and they have typed those chosen proverbs using the proposed asynchronous system illustrated (or) shown in Table 4. The 100% spelling/typing accuracy was obtained from nine subjects.

F. WORKLOAD EVALUATION

The proposed system works in both synchronous and asynchronous modes. To evaluate the subjective workload on each system mode, each subject has completed the NASA-TLX

TABLE 5. Workload evaluation results in each subject.

Subject number	Mental demand		Physical demand		Temporal demand		Effort	
	Synchronous	Asynchronous	Synchronous	Asynchronous	Synchronous	Asynchronous	Synchronous	Asynchronous
S1	2	2	1	1	6	1	6	1
S2	2	1	0	0	5	0	5	0
S3	3	3	2	1	7	0	6	1
S4	2	2	1	1	8	1	4	0
S5	2	2	2	1	8	1	7	0
S6	1	2	1	1	6	0	7	1
S7	2	2	2	1	5	0	5	0
S8	3	3	1	0	7	0	6	0
S9	3	2	2	2	8	1	8	0
S10	1	1	1	1	7	0	8	1
Average	2.1	2	1.3	0.9	6.7	0.4	6.2	0.4

questionnaires (mental demand, physical demand, temporal demand and effort) [37], [38] and the scores (low (0) to high (10)- the scores are normalized between 0 to 10) are reported in Table 5.

The scores of a workload evaluation test were analyzed using paired t test with bonferroni correction. The scores of a synchronous and asynchronous system shows significant difference for temporal demand ($p<0.00000001$) and effort ($p<0.00000001$). The temporal demand is an amount of time pressure involved in completing a task. In synchronous case the subject has to perform an eye movement within a SSVEP time window. If no eye movement is detected within a SSVEP time window, it leads to error. Whereas, in asynchronous case subjects could have control on time, there is no time pressure involved. The subject could perform tasks (eye movement) based on his/her desire, the system won't select any target until the eye movement is performed by the subject.

Effort is how hard does the participant have to work to maintain their level of performance. In asynchronous case the subjects could shift the system mode into active to idle whenever they need rest while doing the experiment. Therefore, the performance level will be higher in asynchronous case. Whereas in synchronous case, the performance will be affected by the subject's fatigue level. The asynchronous system has got less score for workload evaluation as compared to the synchronous system. Therefore, the less score of the asynchronous system indicating that this asynchronous speller system was acceptable to all the subjects.

IV. DISCUSSION

The use of SSVEP and EOG signals in the proposed structure (paradigm) increases the target detection accuracy and ITR and reduces the average target detection time. Since, both the EOG and the SSVEP are detectable at short time length, the idea of using a simultaneous combination of these two signals provides selecting a character in just about 2.71 s (average value). In this 40-character speller, the number of flickering symbols on the screen was decreased from 40 to 5 symbols. Reducing the number of flickering symbols decreases the frequency recognition error by reducing the adverse effects of neighboring flickers which causes the user fatigue. On the other hand, by reducing symbols, increasing the stimulation frequency step is provided which also decreases the error. Finally, it increases the recognition accuracy. On the other hand, target recognition in the proposed SSVEP-EOG speller needs minimal training data which makes this speller more practical for daily life applications.

On the other hand, the simultaneous combination of SSVEP with EOG signal is a novel part of our speller which improves the ITR. The P300 based system is event related and so the occurrence of saccadic eye movement causes some information to be lost, in simultaneous combination of EOG and P300. Because of this limitation, existing EOG-P300 studies have combined these two signals sequentially [16], [21], [24], [27]. This is while the SSVEP response is steady-state and so the simultaneous combination of this signal with the EOG will be efficient. The proposed SSVEP-EOG combination is effective in increasing the ITR and accuracy as compared with sequential EOG-P300 spellers used in state-of-the-art studies available in the literature illustrated in Table 6 (In Table 6, the numbers in the first column refers to the reference cited at the end of this paper).

In this study, a set of online experiments was performed in both synchronous and asynchronous modes. The experimental procedures and results of those online experiments were explained in section 3.3 to 3.5. The ITR and classification accuracy across asynchronous experiments are 116.58 bits/min and 99.38% respectively. The average target detection time across asynchronous experiments is 2.713 seconds. The classification accuracy, ITR and characters per minute of the proposed asynchronous speller system are compared with the existing hybrid speller systems (illustrated in Table 6). From Table 6, we can conclude that the proposed system has achieved high performance metrics as compared to the conventional speller systems.

User-friendliness is a significant factor in the usability evaluation of BCI systems. It is well known that in

TABLE 6. Comparison of the proposed system with conventional speller/keyboard systems.

Reference	Control signals or components	Classification accuracy (%)	ITR (bits/min)	Character per min
[39]	SSVEP	79.3	55.9	-
[40]	SSVEP	90.3	43.8	-
[41]	c-VEPs	97.1	85.7	-
[42]	EEG-RGB	89.7	-	6.4
[43]	EOG-ERD	89.3	24.7	-
[44]	EOG-P300	90.62	18.28	3.4
[22]	EOG-P300	100	57.8	9.6
[21]	EOG-P300	93.6	43.8	-
[20]	SSVEP-EOG	96.73	76.02	16.21
[25]	SSVEP-EOG	98.33	69.21	13.79
[45]	SSVEP-EOG	95.42	105.52	-
[8]	SSVEP-EOG	94.16	71	14
[46]	SSVEP-ET	90.35	190.73	-
[47]	SSVEP-ET	92.1	180.8	-
[48]	SSVEP-RSVP	93.06	23.41	-
[49]	SSVEP-P300	92.30	82.38	-
[50]	EEG-EOG	93.70	45.97	9.74
Proposed System	**SSVEP-EOG**	**99.38**	**116.58**	**22.2**

a SSVEP-based BCI system, the flickering of neighboring non-target symbols may bother individuals and cause fatigue [51]. In this study, decreasing the required symbols on the screen reduced user's eye fatigue. Furthermore, decreasing the workload on the subject by an eye blink is only for target character highlights also reduces the user's eye fatigue. So, both the feature leads to the system became more user friendly. The workload evaluation test scores indicate that subjects were more comfortable with this system. Unlike the existing EOG based HBCI spellers that use the P300 which require a large number of electrodes [21], [22], [44], the SSVEP recording was implemented using fewer electrodes. We also used the eye movement (blink) just along the vertical direction which is realized by only two electrodes (one differential channel). Therefore, our system has a great usability rating in comparison with most existing EEG/EOG-based hybrid BCI systems. The above results states that the proposed asynchronous hybrid SSVEP-EOG system would be the best communication system for real time usage. Though the proposed system outperforms than conventional hybrid spellers, a limitation with this system is portability issue. The proposed speller system needs fixed place and it is not movable. This can be solved by wireless transmission of control signals for making movable real time speller applications. The experimental paradigm is the novel part of the proposed work, an additional eye movement with efficient SSVEP feature extraction techniques in asynchronous SSVEP-EOG system will increases the performance metrics of the speller system.

V. CONCLUSION

This study presents a new online hybrid BCI speller based on the simultaneous combination of SSVEP and EOG. It allows spelling 40 characters by using only five stimulation frequencies. To enhance the system efficiency and reduce the workload on the subjects/uses, an oddball paradigm has been introduced on the speller layout. The average recognition accuracy, ITR and speed of the proposed speller were 99.38%, 116.58 bits/min and 22.2 char/min, respectively. The novel SSVEP-EOG speller achieved acceptable performance in comparison with the state-of-the-art SSVEP, P300 and EOG based hybrid spellers.

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