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Research article

Exploration of illusory visual motion stimuli: An EEG-based brain-computer interface for practical assistive communication systems

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A R T I C L E I N F O

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A B S T R A C T

This paper presents an illusory visual motion stimulus-based brain-computer interface (BCI). We aim to use the proposed system to enhance the motor imagery (MI) modality. Since motor imagery requires a long time for training, a stimulation method with external stimuli through the sensory system is an alternative method for increasing efficiency. The research is divided into two parts. First, we observed the visual motion illusion pattern based on brain topographic maps for the novel BCI modality. Second, we implemented the illusory visual motion stimulus-based BCI system. Arrow and moving-arrow patterns were used to modulate alpha rhythms at the visual and motor cortex. The arrow pattern had an average classification accuracy of approximately 78.5%. Additionally, illusory visual motion stimulus-based BCI systems are proposed using the proposed feature extraction and decision-making algorithm. This proposed BCI system can control the cursor moving in the left or right direction with the designed algorithm to create five commands for assistive communication. Ten volunteers participated in the experiment, and a brain-computer interface system with motor imagery and an illusory visual motion stimulus were used to compare efficiencies. The results showed that the proposed method achieved approximately 4% higher accuracy than motor imagery. The accuracy of the proposed illusory visual motion stimulus and algorithm was approximately 80.3%. Therefore, an illusory visual motion stimulus hybrid BCI system can be incorporated into the MI-based BCI system for beginner motor imagery. Based on the results, the proposed assistive communication system can be used to enhance communication in people with severe disabilities.

1. Introduction

The brain-computer interface (BCI) is a modern technology used for communication between humans and external devices via brain signals [1, 2]. BCIs are widely and continuously used in many kinds of applications, such as biometric, prevention, economic, education, sports, and medical applications, including diagnosis, assistive technology, and rehabilitation [3, 4, 5, 6, 7, 8, 9, 10]. BCIs can be divided into invasive and noninvasive BCIs according to the acquisition technique. Many researchers prefer to develop noninvasive BCIs by using an electroencephalogram (EEG) signal. EEG signals are electric brain signals obtained by placing electrodes on the scalp following the international 10–20 system to measure the summation of neuron potentials. EEG machines are small, flexible and portable, employing a dry electrode with a wireless system. A new EEG machine has high efficiency in measuring and recording signals with a high resolution. Popular EEG features include event-related desynchronization/synchronization (ERD/ERS) via a mental motor imagery (MI) task and visual evoked potentials (VEPs), which are direct responses to visual stimuli through the optic nerve (1). Examples of VEP-BCIs, transient VEPs or P300, and steady-state visual evoked potentials (SSVEPs) [11, 12] can achieve high accuracy and require less time for training. However, like natural thinking, the motor imagery paradigm is still a favorite and challenging topic for BCI research. Mobility enhancements, such as electric wheelchairs and robots controlled via EEG during motor imagery [13, 14], are a popular application for people who have a severe disability. We can collect brain data during imagery tasks, which requires practice to create EEG features, such as ERD/ERS. The MI-based BCI system communicates with devices using imaging of physical movement to generate the signal and convert it into a command to operate the machine. However, the MI-based BCI system is still not suitable for all users. The system requires a training session. To enhance the performance of motor imagery-based BCIs [15,

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16], previous research proposed a novel MI paradigm and integrated motor imagery with other EEG features to create a hybrid BCI system [17, 18, 19, 20, 21, 22, 23, 24]. For example, Horki et al. proposed using ERD and SSVEP for MI-based BCIs and combining a multisensory approach with visual and somatosensory stimulation. Event-related potentials (ERPs) were experimentally determined by placing arms on the table, putting 3 LED lights between the arms at the same distance and applying somatosensory stimulation to both wrists. A flashing LED that approaches the wrist had a higher incidence of stimulation. The results show that visual stimulation is an automatic condition of somatosensory stimulation [17]. Moreover, Allison and team introduced two BCI modalities, motor imagery and steady-state visual evoked potentials (SSVEPs) [18]. The EEG signals were recorded under three conditions: 1) imaging the movement of the left hand or right hand, 2) stimulation with visual attention, and 3) the use of both methods simultaneously. Switching among all three methods can improve accuracy for some of the subjects. The result of this experiment can explain why the hybrid has 81.0% accuracy, while ERD has 74.8% and SSVEP has 76.9%. However, some subjects can improve the accuracy when using the proposed technique because some of them cannot combine two different BCI approaches or one of the signals has high accuracy. Furthermore, Ma et al. [19] explained the combination of motor imagery (MI) and motion-onset visual evoked potential (mVEP) for the new hybrid brain-computer interface system to improve the efficient 2D movement control of a cursor. The results from seven subjects show that the proposed system could evoke the MI and mVEP signals simultaneously, and both were very close to the single-modality BCI task in the offline experiment; the single-modality MI 75% mVEP 85%, and the Multimodality MI 77% mVEP 84%. The online experiment provided more efficient and natural control commands. However, subjects needed to perform multiple tasks simultaneously, and they allocated more attention to MI while gazing at visual stimuli. In addition, Xiaokang et al. [20] proposed unilateral tactile stimulation (Uni-TS) for motor imagery, which was employed in an experiment with two groups of participants: a control group performing motor imagery with both hands and an enhanced group contacting the tactile stimulator with disabled hands and motor imagery. The results indicated that using Uni-TS significantly affects contralateral cortical activation during MI of hand stimulation. The accuracy of this proposed system improved from 72.5% to 84.7%. Moreover, stroke patients in the enhanced group achieved an accuracy of more than 80%. However, this experiment had a small sample of stroke patients, which may not represent patients with tactile sensation problems. Additionally, Sangtae et al. [18] presented a new hybrid brain-computer interface that integrates two different EEG tasks: tactile selective attention using steady-state somatosensory evoked potentials (SSSEPs) and motor imagery using event-related desynchronization (ERD). They divided the experiment into 4 methods: 1) motor imagery paradigm, 2) tactile selective attention paradigm, 3) hybrid paradigm-simultaneous approach, and 4) hybrid paradigm-consecutive approach. The consecutive approach achieved the best performance compared to the other methods. The classification accuracy of this method improved by approximately 10% compared with motor imagery. Moreover, the enhancement paradigm with a moving rubber hand illusion system [22] presented a method for improving ERD using body illusion, also known as the rubber hand illusion, using a motor-driven mechanical hand. In the first experiment, subjects attempted to move the right wrist when a green light appeared on the screen randomly. In the second experiment, the subjects performed the task with the mechanical hand while the real right hand was covered with a blanket to prevent visual feedback. Then, the subjects touched the mechanical and real hands in the same position. When the subjects felt that the mechanical hand was a real hand, they imagined that it was similar to being touched by a real hand. The results improved the ERD method but were not sufficient for motor execution. Therefore, we attempted to investigate a new visual illusion stimulus for motor imagery enhancement. Additionally, BCI system evaluation is influenced by human cognition when performing a motor imagery paradigm. The subjects performed a conventional motor imagery paradigm. After that, they generated an estimate by themselves without receiving feedback and then compared the two values. The subjects accurately predicted the effectiveness of motor imagery-based BCIs [8].

Previous research on the enhancement of motor imagery had four primary purposes: 1) developing feature extraction and classification methods, 2) investigating novel MI paradigms and feedback, 3) developing an approach comprising a user training system, and 4) proposing a hybrid BCI system. In this work, we consider a novel paradigm from human perception to induce motor activity. We employ a phenomenon from illusory motion visual stimulation involving the wheel pattern, arrow pattern, and moving-arrow pattern for an MI-based BCI. The proposed system represents a novel BCI system, and we hope that the proposed system can enhance the communication of people with severe disabilities. Moreover, illusory visual motion stimuli are further integrated with motor imagery for user training sessions. The methods can be divided into two main parts: the investigation of the visual illusory motion stimulus paradigm and brain activity, and the design of illusory motion visual stimulus-based BCIs and evaluation.

2. Proposed methods

2.1. Proposed assumption and visual illusory motion stimulation paradigm

For brain stimulation, depending on the kind of stimulus or paradigm, a brain cortex that responds with a decrease in alpha power (8–12 Hz) is called event-related desynchronization (ERD), or an alpha power increase is called event-related synchronization (ERS). For example, visual attention can generate alpha rhythm at prefrontal and occipital areas. Motor imagery can generate alpha rhythms in frontal and central areas. Furthermore, previous studies observed a flickering wheel illusion pattern by Sokoliuk and VanRullen [25]. They reported that the flickering wheel frequency of visual illusion correlated with the EEG frequency in the alpha band.

We repeated the exploration by using our paradigm and a wheel pattern based on EEG frequency analysis [26]. The wheel pattern consisted of 24 pieces (angle between propeller = 5°), 48 pieces (4°), and 96 pieces (3°) of the propeller with a 5 cm diameter and was used to stimulate the visual and motor cortex. We also found that the number of pieces in the wheel pattern affected the alpha band, and 96 pieces quickly induced a response in the occipital and central areas of the brain. Therefore, we proposed a new illusory motion stimulation paradigm for activating a response in the visual and motor cortexes by using the arrow pattern shown in Figure 1(a), consisting of an illusory motion arrow pattern (picture) and a moving-arrow pattern (video: 5 frames per second) to stimulate the visual cortex and induce the motor to compare both EEG responses. For this assumption, we assumed that by focusing on the illusory motion stimulus pattern such that the eyes are stimulated and the motors are induced in the left/right direction, alpha asymmetry [27] in the central and occipital areas can be observed. We set up a new experiment to explore the paradigm and illusory motion stimulus. The results were used to design the feature extraction method and algorithms to extend the use of our proposed visual illusory motion stimulus patterns and paradigm in a real-time motor imagery-based BCI system.

Using the paradigm shown in Figures 3(a) and (b), two commands were generated using the left and right directions of the arrow by looking at the proposed illusory motion stimulator according to the focusing paradigm. The two commands were performed as 1) both eyes looking at the center of the left-direction arrow for left command and 2) both eyes looking at the center of the right-direction arrow for the right command.

2.2. Preliminary study

In this preliminary experiment, we used a 19-channel Brainmaster Discovery 24E for EEG signal acquisition at a sampling rate of 256 Hz. During preprocessing, the recorded signals were filtered for power line

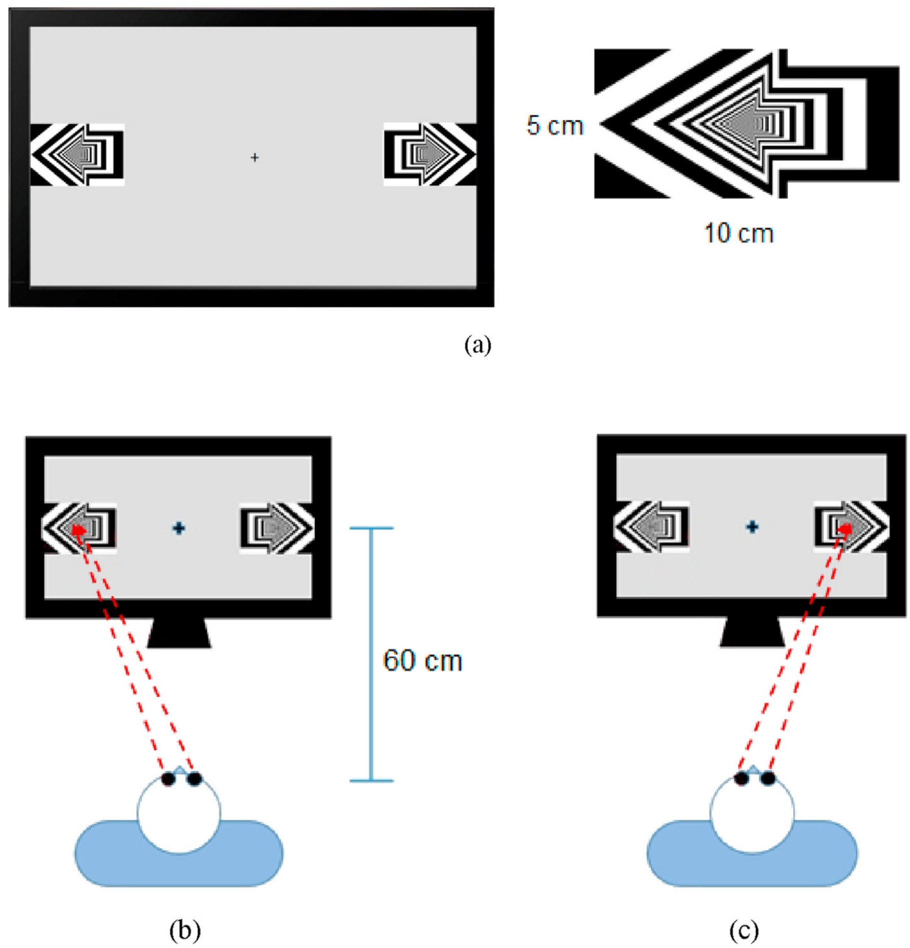

Figure 1. (a) Arrow pattern for illusory motion stimulation. (b) Focusing paradigm on the left arrow for inducing the right visual and motor cortex. (c) Focusing paradigm on the right arrow for inducing the left visual and motor cortex.

noise by a 50-Hz notch filter, and a 2-Hz to 40-Hz bandpass digital filter was used for motion artifact removal. Seven healthy subjects (mean age 22 ± 3.4 years) participated in the experiment by following the task sequence, as illustrated in Figure 2. A single trial consisted of four events, starting with focusing at fixation (+) for EEG baseline collection over 5 s. Then, the subject rested for 3 s. After that, the subject stared at the left or right arrow illusory motion visual stimulator for 5 s. Finally, the subject rested for 3 s. The subjects performed the same sequences in Figure 2 for moving the arrow illusory motion visual stimulator (video). Each subject randomly performed left and right commands, with 20 trials per stimulus pattern and 80 trials for each subject.

NeuroGuide software was employed to visualize the brain response during alpha rhythm (including sensorimotor rhythm and visual attention response) signal analysis. This software provides dynamic normative EEG comparisons in real time during editing and automatic artifact rejection and has been used for clinical and research purposes [28]. According to the grand-averaged brain topographic mapping of the FFT absolute power for all subjects, we visually observed the feature pattern

+	**Rest**	**Left/Right arrow motion illusion stimulus**
5 seconds	3 seconds	5 seconds

Figure 2. Task experiment for visual illusory motion stimulation.

for each illusory motion pattern (Figure 3 and Figure 4). The brain areas of interest were the central, parietal, and occipital areas. We found that the brain response occurred through visual attention and motor intention.

Nonmoving-arrow pattern: For the left-direction stimulus, we observed that the right central (C4), right parietal (P4), and left occipital (O2) regions exhibited a greater response in the alpha band (8–12 Hz), as shown in Figure 3(a) and Figure 4(a) for subjects 1 and 2, respectively. In contrast, for the right-direction stimulus, we observed that the left central (C3), left parietal (P3), and left occipital (O1) regions exhibited a greater response in the alpha band (8–12 Hz), as shown in Figure 3(b) and Figure 4(b) for subjects 1 and 2, respectively.

Moving-arrow pattern: For the left-direction stimulus, we observed that only the left occipital (O2) exhibited a greater response in the alpha band (8–12 Hz), as shown in Figure 3(c) and Figure 4(c) for subjects 1 and 2, respectively. For the right-direction stimulus, we also observed that only the left occipital (O1) exhibited a greater response in the alpha band (8–12 Hz), as shown in Figure 3(d) and Figure 4(d) for subjects 1 and 2, respectively.

2.3. Proposed BCI system based on an illusory motion stimulus

We employed the results in section 2.2 to propose an illusory motion stimulation-based BCI system for enhancing motor imagery, as shown in Figure 5. We selected the arrow illusory motion pattern and paradigm (Figure 1). According to the preliminary results, we designed an algorithm to extract features to classify EEG signals into left/right commands to control the cursor of the proposed assistive communication system

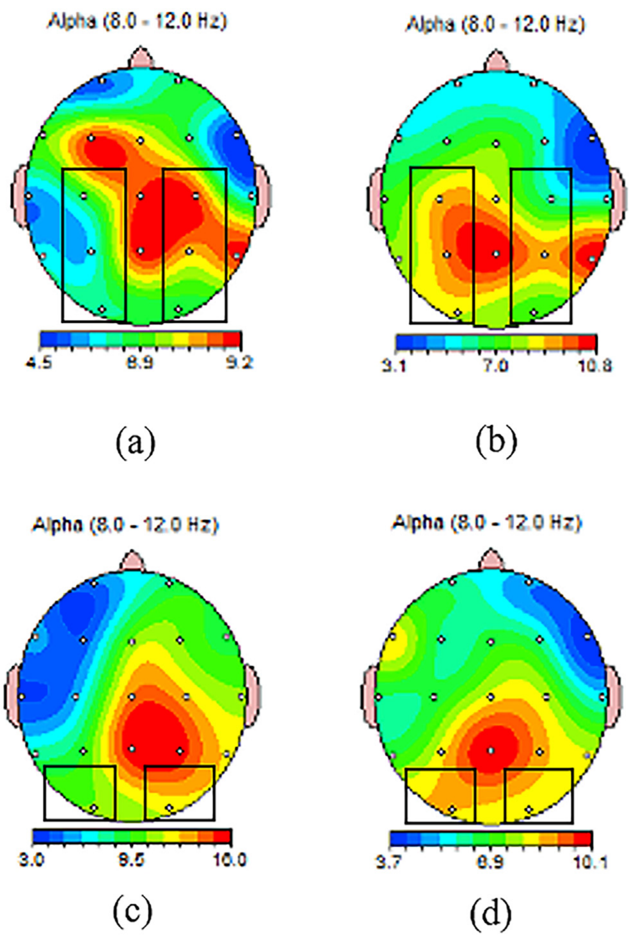

Figure 3. Example brain topographic maps for the visual illusory motion stimulus in representative subject 1. (a) Illusory motion stimulation with the left arrow, (b) illusory motion stimulation with the right arrow, (c) illusory motion stimulation with the left-moving arrow, and (d) illusory motion stimulation with the right-moving arrow.

(Figure 6(b)). We also used the visual-based bar graph level indicator to feedback the response and guided the user to achieve high efficiency for user practice.

2.4. Illusory visual motion stimulus-based BCI for a practical assistive communication system

Using the proposed system with the arrow pattern and paradigm in Figure 1(b) and (c), we implemented a real-time illusory visual motion stimulus-based BCI system for cursor control via a left/right arrow illusory motion stimulator (Figure 6(b)). Five choices were selected by moving the cursor in the left or right direction by following the diagram in Figure 6(a).

Before commanding the system, the red circle in the middle was activated as the default command. Then, the user moved the cursor in the left or right direction to make a request. Additionally, the caretaker could input other pictures or word questions and answers to communicate with the user. The user instructions were summarized as follows:

1) User calibration was performed by following section 3.3.
2) The user stared at the left or right arrow illusory motion stimulator to move the cursor in the left or right direction to stop at the desired command.
3) The caretaker responded to the requirement and presses the red button to reset.

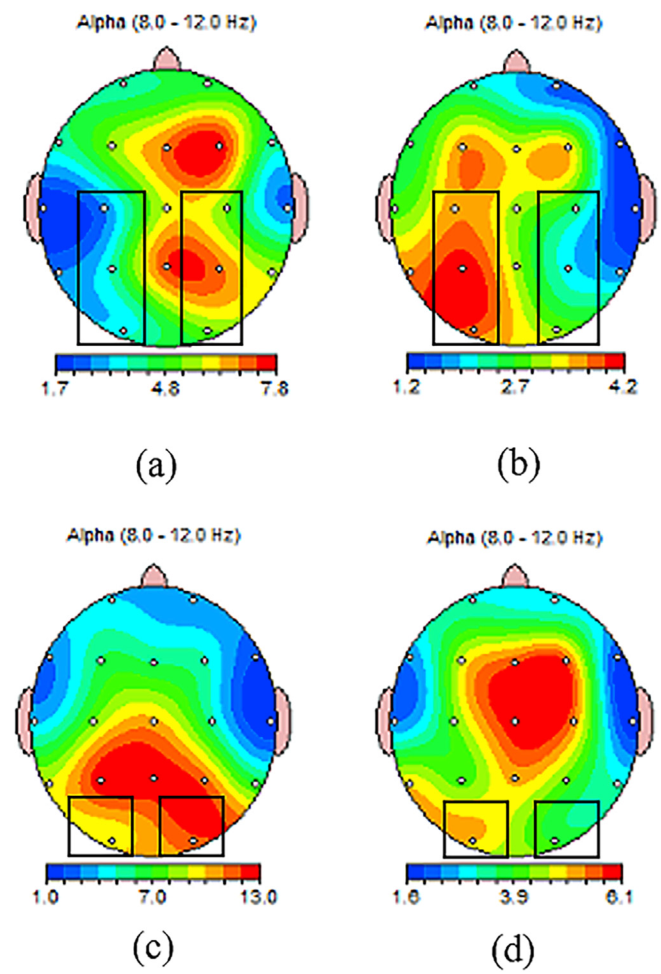

Figure 4. Example brain topographic maps for the visual illusory motion stimulus in representative subject 2. (a) Illusory motion stimulation with the left arrow, (b) illusory motion stimulation with the right arrow, (c) illusory motion stimulation with the left-moving arrow, and (d) illusory motion stimulation with the right-moving arrow.

3. The real-time illusory visual motion stimulus-based BCI system

3.1. EEG acquisition

Based on the results from section 2, two bipolar channels, O1–C3 and O2–C4, were acquired using a BIOPAC™ system EEG amplifier. The electrode positions followed the international 10–20 electrode placement system. The acquired signals were filtered by an analog bandpass filter with cutoff frequencies at 1 and 35 Hz to avoid artifacts. A 50 Hz analog

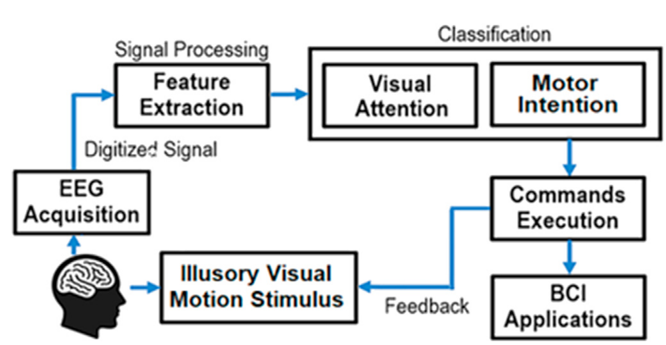

Figure 5. The proposed BC system based on an illusory motion stimulus.

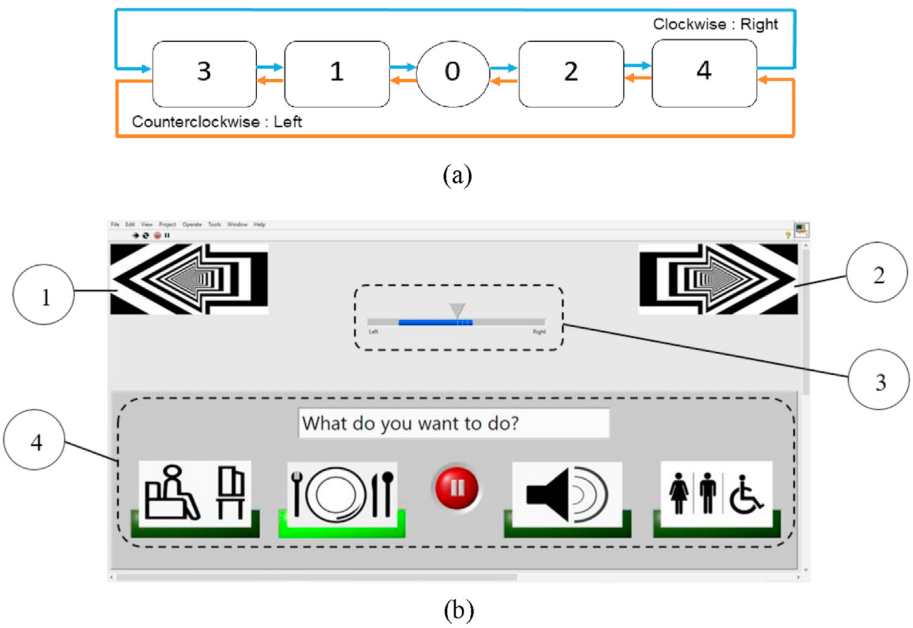

Figure 6. The real-time illusory visual motion stimulus-based BCI system for controlling the cursor of the assistive communication system. (a) Decision flowchart for the direction of cursor movement. (b) Graphic user interface (GUI) consisting of a 1) left arrow illusory motion stimulator, 2) right arrow illusory motion stimulator, 3) bar graph for visual feedback, and 4) the communication panel contains one message box for the question by typing and four choices with pictures or words for answering that were defined by the caretaker. The patient performed choice selection with cursor control.

notch filter was used to remove power line noise. For analog-to-digital A/D conversion, a National Instrument (NI) USB 6009 multifunction data acquisition card was used with a sampling rate of 256 Hz to convert the analog signals to digital data. A 3–35 Hz digital bandpass filter was used to remove power line noise and motion artifacts. This study protocol was approved by the Institutional Review Board (IRB) of Mahidol University in compliance with the Declaration of Helsinki, The Belmont Report, CIOM Guidelines and the International Conference on Harmonization in Good Clinical Practice (ICH-GCP): MU-CIRB 2017/037.2802. Written informed consent was obtained from all participants prior to participating in this study.

3.2. Feature extraction and decision-making algorithms

For the proposed real-time BCI system, a simple signal processing and decision-making algorithm for visual attention and motor intention detection using Welch's periodogram method algorithm was performed for fast computations [29, 30].

1) Calibration: Before using the proposed system, baseline parameters were collected while the user looked at a blank screen for 4 s five times.

B_{O1} was defined as the baseline relative alpha power in EEG channels O1–C3, and B_{O2} was defined as the baseline relative alpha power in EEG channels O2–C4, which were calculated as:

$$B_{O1} = 1.25^*(B_{O1}(\alpha)/(B_{O1}(\theta) + B_{O1}(\alpha) + B_{O1}(\beta)) \quad (1)$$

$$B_{O2} = 1.25^*(B_{O2}(\alpha)/(B_{O2}(\theta) + B_{O2}(\alpha) + B_{O2}(\beta)) \quad (2)$$

where $B_{O1}(\theta)$, $B_{O1}(\alpha)$ and $B_{O1}(\beta)$ are the absolute power of the PSDs in EEG channels O1–C3 and $B_{O2}(\theta)$, $B_{O2}(\alpha)$ and $B_{O2}(\beta)$ are the absolute power of the PSDs in EEG channels O2–C4. For each EEG frequency band used [20], e.g., theta (θ): 4–7 Hz, alpha (α): 8–12 Hz and theta (θ): 13–25 Hz, we did not use the delta band (1–3 Hz), as this band may overlap with the motion artifact.

2) Feature Extraction: D_{O1} are the differences in relative alpha power between RP_{O1} and B_{O1}, and D_{O2} are the differences in relative alpha power between RP_{O2} and B_{O2}. According to our assumption, the alpha band should increase. Hence, the index was defined to allow the difference level to be greater than 0.25, to multiply B_{O1} and B_{O2} by 1.25 as the threshold for making the decision to calculate the parameters D_{O1} and D_{O2}, and by the following:

$$D_{O1} = \begin{cases} (RP_{O1} - B_{O1}) & , RP_{O1} - B_{O1} > 0 \\ 0 & , RP_{O1} - B_{O1} < 0 \end{cases} \quad (3)$$

$$D_{O2} = \begin{cases} (RP_{O2} - B_{O2}) & , RP_{O2} - B_{O2} > 0 \\ 0 & , RP_{O2} - B_{O2} < 0 \end{cases} \quad (4)$$

Of the EEG features acquired during stimulation, RPO1 is the relative power spectral density (PSD) of the alpha band of the EEG signals from the O1 position, and RPO2 is the relative PSDs of the alpha bands of the EEG signals from the O2 position, which are calculated as:

$$RP_{O1} = P_{O1}(\alpha)/(P_{O1}(\theta) + P_{O1}(\alpha) + P_{O1}(\beta)) \quad (5)$$

$$RP_{O2} = P_{O2}(\alpha)/(P_{O2}(\theta) + P_{O2}(\alpha) + P_{O2}(\beta)) \quad (6)$$

where $P_{O1}(\theta)$, $P_{O1}(\alpha)$ and $P_{O1}(\beta)$ are the magnitudes of the PSDs of the real-time acquired EEGs in channels O1–C3. $P_{O2}(\theta)$, $P_{O2}(\alpha)$ and $P_{O2}(\beta)$ are

Figure 7. Experimental setup.

Table 1. The task for testing the system.

Sequences	1	2	3	4	5	6	7	8	9	10
Command	R	L	R	R	L	R	L	R	L	L

Note: R = right and L = left.

Table 2. Results of the left/right commands of the arrow and moving-arrow illusory motion stimulation pattern.

Illusory motion stimulation	Average classification accuracy (%)			
	Arrow pattern		Moving-arrow pattern	
Subjects	Left (L)	Right (R)	Left (L)	Right (R)
1	85	75	70	75
2	80	75	80	70
3	90	85	85	80
4	80	80	65	75
5	75	70	75	70
6	85	80	80	80
7	70	65	70	60
8	75	80	75	70
9	75	80	80	75
10	85	80	70	75
Mean ± S.D	80 ± 5.77	77 ± 5.87	75 ± 6.24	73 ± 5.87

Table 3. Results of the real-time illusory visual motion stimulus-based BCI system for the assistive communication system.

BCI methods	% Average Accuracy			
	Motor Imagery		Proposed Method	
Subjects	1st time	2nd time	1st time	2nd time
1	70.0	80.0	73.3	83.3
2	66.7	76.7	76.7	80.0
3	60.0	66.7	66.7	73.3
4	70.0	66.7	76.7	80.0
5	76.7	76.7	73.3	76.7
6	80.0	86.7	86.7	83.3
7	73.3	80.0	76.7	73.3
8	70.0	73.3	73.3	80.0
9	76.7	80.0	83.3	90.0
10	73.3	73.3	83.3	83.3
Mean ± S.D.	71.7 ± 5.72	76.0 ± 6.25	77.0 ± 5.97	80.3 ± 5.08

the magnitudes of the PSDs of the real-time acquired EEGs in channel O2–C4.

3) Decision Making: We used a simple decision rule to compare D_{O1} and D_{O2}. The two-class classification decision (right or left command) was generated according to:
   if $D_{O1} < D_{O2}$, Decision is "Left"
   if $D_{O1} > D_{O2}$, Decision is "Right"
   if $D_{O1} = D_{O2} = 0$, No Decision.

4. Experiments

4.1. Experiment I: performance evaluation of the arrow and moving-arrow illusory motion stimulation pattern and the proposed algorithms

Ten healthy subjects (mean age 24 ± 3.8 years) without any BCI experiences were enrolled. The experimental cue was defined by randomly asking the subject to stare at the center of each stimulator (left arrow or right arrow) for 5 s to create an output command using the proposed algorithm to detect and automatically calculate the accuracy. Each subject performed 40 trials (20 trials for the left stimulus and 20 trials for the right stimulus) by following the paradigm in Figure 1(b) and (c).

4.2. Experiment II: performance of illusory visual motion stimulus-based BCI for a practical assistive communication system

Ten healthy subjects from the previous experiment, seven of whom had no experience with real-time BCIs, participated in this experiment (Figure 7). All subjects were trained for 20 min on how to perform the illusory visual motion stimulus-based BCI system. Each subject performed three trials per day. For each trial, there were 10 commands. Each subject performed motor imagery and visual motion stimulation to control the cursor following the sequence in Table 1. The experiment consisted of two days for user performance verification. The classification accuracy is reported in Table 3.

5. Results and discussions

According to the results in Table 2, by using our proposed algorithm, the average classification accuracy of the proposed system for individual commands ranged from 65% to 90%, the maximum accuracy was achieved by the arrow pattern, and the average accuracy of the arrow pattern was 80% and 77% for the individual left and right commands, respectively. Compared with previous works, the performance of the arrow pattern ranged from the previous visual modality to combined MI as combining motor imagery and moving onset, 77%–84% [19]. The moving-arrow stimulus pattern yielded slightly lower accuracy. Moreover, using the moving-arrow pattern can easily induce eye fatigue in the subject. Therefore, we employed the arrow pattern for illusory motion visual stimulus-based BCI for a practical assistive communication system.

According to the results in Table 3, two issues were listed. The first is the efficiency of BCI methods. The maximum average accuracy of the motor imagery was 76.0%, and the average accuracy of the proposed method was 80.3% from the second time of the experiment (the next day). The proposed illusory visual motion stimulus can yield higher maximum accuracy than motor imagery, at approximately 4%.

The second issue considers user performance. In the first experiment, the average accuracy of motor imagery ranged from 60% to 80%, and the average accuracy of the proposed method ranged from 66.7% to 86.7%. In the second experiment, the average accuracy of motor imagery ranged from 73.3% to 83.3%, and the average accuracy of the proposed method ranged from 73.3% to 90%. The proposed method achieved high accuracy for the first time. However, with user progression, motor imagery can increase the accuracy to exceed that of the proposed methods. Individual subjects reported equivalent results between the motor imagery and illusory visual motion stimulus methods.

Following the preliminary study to verify our assumption of using illusory visual motion stimulation for brain-computer interfaces, brain topographic maps of the illusory visual motion stimulus indicated an asymmetry of central and occipital areas. Following the preliminary result, we intend to verify the assumption by including additional participants. In addition, we generate a protocol for the users of the proposed illusory visual motion stimulus-based BCI systems. Experiment I indicated that the arrow illusory motion stimulation pattern (picture) provides a better stimulus than the moving-arrow illusory motion stimulation pattern (video) and for the proposed feature extraction and decision-making algorithm. With the use of motor imagery, some users may have difficulty performing and need time for training. Hence, using illusory visual motion stimulation can induce motor areas and can create two commands. This can be added to additional motor imagery-based BCI systems. Finally, an application in real-time assistive communication manipulation was demonstrated in Experiment II, and acceptable accuracies were obtained.

6. Conclusions

In this study, we proposed an illusory motion visual stimulus pattern for a practical assistive communication system. To explore our proposed illusory visual motion stimulus for brain-computer interfaces in section 2, brain topographic maps for the visual and motor intention in the left and right directions initially displayed asymmetry of the occipital and central areas on the opposite side of the stimulus direction. The central area (C3 and C4), which is a motor function area, is an efficient reference electrode that can acquire bipolar EEG signals on each side of the visual area (occipital area) for visual motor intention detection. Section 3 shows that the nonmoving-arrow pattern (picture) is more user-friendly than the moving-arrow illusory motion stimulus pattern (video) for verifying the proposed feature selection and decision-making algorithm. We also generated a protocol for users of the proposed illusory visual motion stimulus-based BCI. Finally, the real-time practical assistive communication system was demonstrated in section 4, and user-friendliness was obtained. The proposed application can be used for communication enhancement in people with severe disabilities. Furthermore, we conclude that the illusory visual motion stimulus method can be used for a real-time BCI system and can also be further employed to increase the efficiency of motor imagery.

7. Limitations

Some limitations of illusory visual motion stimulus-based BCI systems when applied to assistive communication systems should be reported:

1) Following the initial verification of illusory visual motion stimuli with a small number of subjects, we aimed to further examine additional subjects.
2) To use the proposed system, some subjects could not see the illusion movement within the arrow every time within a short period of time, which can cause a low iteration transfer rate (ITR).
3) For multicommand BCIs, the proposed system yielded lower efficiency than VEP-based BCIs (P300 and SSVEP). Nevertheless, natural actions such as the thought of moving the left hand or right hand and left or right visual spatial attention are still popular for a BCI system. With two commands creation, "yes" or "no," the proposed achieved acceptable efficiency for assistive technology for communication.

Declarations

Author contribution statement

Yunyong Punsawad: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Nannaphat Siribunyaphat: Performed the experiments; Analyzed and interpreted the data; Wrote the paper.

Yodchanan Wongsawat: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

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Data availability statement

Data included in article/supplementary material/referenced in article.

Declaration of interests statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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References

[1] J.R. Wolpaw, et al., Brain-computer interfaces for communication and control, J. Clin. Neurophysiol. 113 (6) (Jun 2002) 767–791.

[2] G. Papanastasiou, et al., Brain computer interface based applications for training and rehabilitation of students with neurodevelopmental disorders. A literature review, Heliyon 6 (9) (September 2020), 1-13.

[3] I. Lazarou, et al., EEG-based brain–computer interfaces for communication and rehabilitation of people with motor impairment: a novel approach of the 21st century, Front. Hum. Neurosci. 12 (14) (2018).
[4] J.J. Daly, J.E. Huggins, Brain-computer interface: current and emerging rehabilitation applications, Arch. Phys. Med. Rehabil. 96 (3 Suppl) (March 2015) S1–S7.
[5] U. Chaudhary, N. Mrachacz-Kersting, N. Birbaumer, Neuropsychological and neurophysiological aspects of brain-computer-interface (BCI) control in paralysis, J. Physiol. (Feb 2020).
[6] M. Spüler, Questioning the evidence for BCI-based communication in the complete locked-in state, PLoS Biol. 17 (4) (Apr 2019), e2004750.
[7] C.H. Han, et al., Electroencephalography-based endogenous brain-computer interface for online communication with a completely locked-in patient, J. NeuroEng. Rehabil. 30 (1) (Jan 2019) 18.
[8] A. Larson, J. Herrera, K. George, A. Matthews, Electrooculography based electronic communication device for individuals with ALS, in: 2017 IEEE Sensors Applications Symposium (SAS), 2017, pp. 1–5.
[9] F.A. Purva Sharma, S.B. Yash Jobanputra, Augmentative and assistive communication in patients of locked-in syndrome: a case Report, in: W. Jensen, O. Andersen, M. Akay (Eds.), Replace, Repair, Restore, Relieve – Bridging Clinical and Engineering Solutions in Neurorehabilitation. Biosystems & Biorobotics, 7, Springer, Cham, 2014, pp. 735–740.
[10] L. Nita, R.G. Bozomitu, R.G. Lupu, A. Pasarica, C. Rotariu, Assistive communication system for patients with severe neuromotor disabilities, in: 2015 E-Health and Bioengineering Conference (EHB), 2015, pp. 1–4.
[11] F.B. Vialatte, M. Maurice, J. Dauwels, A. Cichocki, Steady-state visually evoked potentials: focus on essential paradigms and future perspectives, Prog. Neurobiol. 90 (4) (Apr 2010) 418–438.
[12] H. Cecotti, I. Volosyak, A. Graser, Evaluation of an SSVEP based Brain-Computer Interface on the command and application levels, in: 2009 4th International IEEE/EMBS Conference on Neural Engineering, 2009, pp. 474–477.
[13] Y. Yu, et al., Self-paced operation of a wheelchair based on a hybrid brain-computer interface combining motor imagery and P300 potential, IEEE Trans. Neural Syst. Rehabil. Eng. 25 (12) (Dec. 2017) 2516–2526.
[14] H. Wang, A. Bezerianos, Brain-controlled wheelchair controlled by sustained and brief motor imagery BCIs, Electron. Lett. 53 (7) (2017) 1178–1180.
[15] T. Yu, et al., Enhanced motor imagery training using a hybrid BCI with feedback, IEEE (Inst. Electr. Electron. Eng.) Trans. Biomed. Eng. 62 (7) (July 2015) 1706–1717.
[16] A. Minkyu, C. Hohyun, A. Sangtae, C.J. Sung, User's self-prediction of performance in motor imagery brain-computer interface, Front. Neurosci. (Feb 2018) 59–71.
[17] P. Horki, T. Solis-Escalante, C. Neuper, G. Muller-Putz, Combined motor imagery and SSVEP based BCI control of 2 DoF artificial upper limb, Med. Biol. Eng. Comput. 49 (May 2011) 567–577.
[18] B. Z Allison, et al., Toward a hybrid brain-computer interface based on imagined movement and visual attention, J. Neural. Eng. 7 (2) (April 2010) 26007.
[19] T. Ma, et al., The hybrid BCI system for movement control by combining motor imagery and moving onset visual evoked potential, J. Neural. Eng. 14 (2) (Apr 2017) 1–20.
[20] S. Xiaokang, Y. Lin, S. Xinjun, Z. Dingguo, Z. Xiangyang, Enhanced motor imagery-based BCI performance via tactile stimulation on unilateral hand, Front. Hum. Neurosci. 11 (2017) 585.
[21] A. Sangtae, A. Minkyu, C. Hohyun, C.J. Sung, Achieving a hybrid brain-computer interface with tactile selective attention and motor imagery, J. Neural. Eng. 11 (6) (Dec 2014) 1–14.
[22] M. Song, J. Kim, A paradigm to enhance motor imagery using rubber hand illusion induced by visuo-tactile stimulus, IEEE Trans. Neural Syst. Rehabil. Eng. 27 (3) (Mar 2019) 477–486.
[23] P. Verma, et al., Performance investigation of brain-computer interfaces that combine EEG and fNIRS for motor imagery tasks, in: 2019 IEEE International Conference on Systems, Man and Cybernetics (SMC), 2019, pp. 259–263.
[24] T. Kimura, j. Katayama, Regularity of approaching visual stimuli influences spatial expectations for subsequent somatosensory stimuli, Exp. Brain Res. 235 (6) (2017) 1657–1663.
[25] R. Sokoliuk, R. VanRullen, The flickering wheel illusion: when α rhythms make a static wheel flicker, J. Neurosci. 14 (33) (2013) 13498–13504.
[26] Y. Punsawad, N. Siribunyaphat, Y. Wongsawat, Self-flickering visual stimulus based on visual illusion for SSVEP-based BCI system, in: 2018 11th Biomedical Engineering International Conference (BMEiCON), 2018, pp. 1–4.
[27] D.L. Rhodes, L.C. Robertson, Visual field asymmetries and allocation of attention in visual scenes, Brain Cognit. 50 (1) (2002) 95–115.
[28] R.L. Cannon, et al., Reliability of quantitative EEG (qEEG) measures and LORETA current source density at 30 days, Neurosci. Lett. 518 (1) (2012) 27–31.
[29] B.S. Zainuddin, Z. Hussain, I.S. Isa, Alpha and beta EEG brainwave signal classification technique: a conceptual study, in: 2014 IEEE 10th International Colloquium on Signal Processing and its Applications, 2014, pp. 233–237.
[30] M.K. Mukul, R. Prasad, F. Matsuno, Relative spectral power and power spectral density changes in motor rhythm for movement imagination, in: 2009 ICCAS-SICE, 2009, pp. 1611–1616.