A Word Communication System with Partner Assist for Amyotrophic Lateral Sclerosis Patients in Late Stages

K. Ozawa, M. Naito, N. Tanaka, and S. Wada

Abstract— **People with severe physical impairment such as amyotrophic lateral sclerosis (ALS) in a completely locked-in state (CLIS) suffer from inability to express their thoughts to others. To solve this problem, many brain-computer interface (BCI) systems have been developed, but they have not proven sufficient for CLIS. In this paper, we propose a word communication system: a BCI with partner assist, in which partners play an active role in helping patients express a word. We report here that five ALS patients in late stages (one in CLIS and four almost in CLIS) succeeded in expressing their own words (in Japanese) in response to wh-questions that could not be answered "yes/no." Each subject sequentially selected vowels (maximum three) contained in the word that he or she wanted to express, by using a "yes/no" communication aid based on near-infrared spectroscopy. Then, a partner entered the selected vowels into a dictionary with vowel entries, which returned candidate words having those vowels. When there were no appropriate words, the partner changed one vowel and searched again or started over from the beginning. When an appropriate word was selected, it was confirmed by the subject via "yes/no" answers. Two subjects confirmed the selected word six times out of eight (credibility of 91.0% by a statistical measure); two subjects, including the one in CLIS, did so five times out of eight (74.6%); and one subject did so three times out of four (81.3%). We have thus taken the first step toward a practical word communication system for such patients.**

Index Terms— **Amyotrophic lateral sclerosis (ALS), brain-computer interfaces (BCI), partner assist, communication aids, completely locked-in state (CLIS), human computer interaction (HCI), near infrared spectroscopy (NIRS), word expression.**

I. Introduction

COMMUNICATION is essential for anyone to fully live life. However, the communication abilities of people with amyotrophic lateral sclerosis (ALS) are severely restricted. ALS is a progressive motor neuron disease: people with ALS gradually lose voluntary control of their muscles and transit to a locked-in state (LIS) in which they are almost completely paralyzed, with residual control over a few muscles such as the eye muscles, which are usually the last ones an ALS patient can control voluntarily [1], [2], [3]. Such patients have great difficulty in communication. The extreme case of LIS is the completely locked-in state (CLIS), in which all motor control (including control of the eye muscles) is lost [1], [2]. Patients in CLIS lose any usual, muscle-based means of communication. For these people, a brain-computer interface (BCI) can provide muscle-independent communication. Although the ultimate success of BCIs will depend on the development of systems that are useful to people with severe disabilities [4], no report has been published on CLIS patients successfully communicating beyond binary "yes/no"-type responses.

Patients in CLIS or on the verge of CLIS cannot even express "yes/no" responses by ordinary means. Moreover, from the viewpoint of communication, such people's answers should not be limited to "yes/no." Accordingly, research has been conducted to enable spelling of words by using various types of electroencephalography- (EEG-) based BCIs [5], [6], [7]. In 1999, using slow cortical potentials, Birbaumer et al. obtained full written messages from two ALS patients in LIS [8]. Many EEG-based BCIs use event-related potentials such as P300 with visual stimuli. It is usually impossible, however, for patients in CLIS or on the verge of CLIS to see a letter matrix because of their drooping eyelids and loss of gaze fixation. Therefore, spelling systems using auditory stimuli [9], [10], [11] and tactile stimuli [12], [13] have been proposed. There are also studies on selecting Japanese kana characters, which we also address in the present study [14], [15]. Functional near-infrared spectroscopy (fNIRS) is another relatively new modality for BCI applications. An fNIRS-based BCI was first proposed by Coyle et al. [16], and its feasibility was tested by Sitaram et al. [17]. Since then, many studies on fNIRS-based BCIs have been published, as described in the reviews by Naseer and Hong [18] and Hong et al. [19].

The majority of these works reported results for healthy people or patients who had ALS but were not in late stages; in contrast, few studies have reported results for patients in CLIS or on the verge of CLIS. While the essential difficulty of

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communication with patients in CLIS has been discussed [20], [21], [22], [23], ALS patients in CLIS still have high cognitive functions, as shown by Fuchino et al. by using fNIRS [24]. Accordingly, the challenge is to improve the quality of life of patients in CLIS or on the verge of CLIS by ensuring that they can benefit from BCIs. Naito et al. [25] reported that 40% of CLIS-ALS patients (7 out of 17) could give "yes/no" responses with an average accuracy of 80% by changing their brain activity while using an fNIRS-based BCI. Jackson et al. [26] performed a year-long field study in the home environment with 26 locked-in ALS patients by using almost the same BCI system used by Naito et al. and confirmed the approach's long-term effectiveness. Gallegos-Ayala et al. [27] reported on one CLIS-ALS patient who used an fNIRS-based BCI over a long term. The patient answered "yes/no" questions over many sessions with an average accuracy of 70%, which is significantly above the chance level. Using a vibro-tactile P300 BCI, Guger et al. [28] reported that two CLIS-ALS patients (out of three) answered "yes/no" questions with accuracies of 90% and 70%, respectively. Okahara et al. [29] succeeded in obtaining binary responses above the chance level from a CLIS-ALS patient by using steady-state visually evoked potentials of the scalp EEG. Han et al. [30] used features calculated from EEG data via Riemannian geometry and achieved a classification accuracy of 87.5% when a CLIS-ALS patient performed mental tasks. Borgheai et al. [31] proposed a visuo-mental paradigm for fNIRS-based BCIs. They showed that the hemodynamic response due to the task was enhanced in the patients, including an ALS patient who lost eye movement, and obtained high classification accuracy above the chance level within short times. Hosni et al. [32] pointed out the importance of optimizing parameters such as the features extracted from the hemodynamic waveforms obtained by fNIRS and the time window for each individual patient. Tonin et al. [33] reported that ALS patients in transition from LIS to CLIS could form complete sentences and communicate independently and freely by using an auditory electrooculogram-based BCI speller system equipped with a word predictor. One patient, however, could not use the system in a follow-up one year later because of the complete loss of oculomotor control.

For ALS patients in CLIS or on the verge of CLIS, all studies except one [33] have reported binary communication like "yes/no" responses to simple questions; there is no report of CLIS patients spelling beyond "yes/no" answers. One reason is that the burden of selecting letters is very heavy for severely locked-in patients. For example, they are expected to perform too many steps to correctly choose the row and column (for the consonant and vowel, respectively, in Japanese) in a letter matrix, which tends to result in choosing wrong letters and having to correct misspellings.

Therefore, we propose a practical online Japanese word communication system for home use that consists of a "yes/no" communication aid using near-infrared light and a special dictionary with vowel entries. The system only requires a patient to choose three vowels and then answer "yes/no" to candidate words including those vowels. To share the burden of spelling words, partner assist is essential for this system. Specifically, the system requires partners such as family members, caregivers, and friends to select an appropriate word in the dictionary, to change one vowel when an appropriate word is not found, and to start over from choosing three vowels when the patient denies an appropriate word. In the ideal form of communication, patients in severe LIS would form full sentences freely by themselves, independently of partners in their homes. However, because that approach is difficult and the issue is urgent, a communication system in which partners and patients cooperate could be a feasible approach to enhance their daily communication before reaching the final goal. In such a system, the process of communication becomes a kind of conversation between patients and partners, which is expected to strengthen the ties between them.

In this paper, we report experimental results of using this system with four ALS patients almost in CLIS (equivalent to a minimal communication state defined as "severely reduced speed and delay in initiation of voluntary functions" [34]) and one patient in CLIS. By cooperating with their partners, the subjects successfully expressed words in response to wh-questions such as "What is your favorite animal?" The system is also applicable to alphabetic languages. A preliminary version of this article was published in arXiv [35].

II. METHODS

A. Subjects

Five ALS patients were recruited as listed in Table I. Subject D was female and the others were male. The mean age was 59.8 years old (SD of 19.6 years old). Subject C was in CLIS and the others were almost in CLIS. The patients that were almost in CLIS had extreme difficulty in communication relying on any voluntary muscle control, and they were unable to have reliable communication with other people. Throughout the experiments, subject C showed no voluntary muscle control, including eye movement, and was diagnosed with CLIS by an experienced neurologist shortly after the experiments. At the age shown listed in column (d), the patients lost any means of reliable communication; until then, they had relied on the functions listed in parentheses.

TABLE I
SUBJECTS

Subject	Age				Stage at Experiments
	(a)	(b)	(c)	(d)	
A	71	54	55	68 (blink)	almost in CLIS
B	51	35	37	48 (third finger & eye)	almost in CLIS
C	30	17	18	27 (mouth corner)	CLIS
D*	67	62	64	66 (blink)	almost in CLIS
E	78	70	71	77 (mouth corner)	almost in CLIS

(a): Age at the time of the word expression experiments in this report.
(b): Age of diagnosis with ALS.
(c): Age of being put on an artificial respirator and becoming unable to speak.
(d): Age when answering "yes/no" became difficult. The patients had relied on the body functions listed in parentheses until then.
*: Female (others: male).

The study was approved by the Toyo University Ethical Review Board for Medical and Health Research Involving Human Subjects and the Institutional Review Board of the Public Health Research Foundation. Informed consent was obtained from the legal representatives in the subjects' families beforehand. Written, informed consent was also obtained from the patients' legal guardians for the publication of any potentially identifiable images or data included in this article.

B. Word Communication

1) Outline of Proposed System

The Japanese kana syllabary consists of five vowels, A, I, U, E, and O; 14 consonants, K, S, T, N, H, M, Y, R, W, B, D, G, P, and Z; and a special letter "NN" that occurs without a vowel. Every Japanese kana character other than a vowel or NN consists of a consonant and a vowel. If a patient tries expressing a word consisting of three Japanese characters without any cooperation, for example, he or she will need to get a correct "yes/no" classification as many as 25.5 times (8.5 times for each character: 3 plus 5.5 times in the 5 x 10 matrix of the Japanese kana syllabary), which will make it virtually impossible to reach the true word.

Fig. 1 shows the framework of the proposed word communication system. It consists of a "yes/no" communication aid, a dictionary with vowel entries, a patient, and a partner. The communication aid is "Shin Kokoro Gatari" ("New Heart Teller," a product of Double Research and Development Co., Ltd, 2016). We prepared a new dictionary that returns words containing input vowels. The dictionary receives three vowels as input and returns the words containing them in the given order. For example, if a sequence "E, I, A" is input, then the dictionary returns 125 words, such as ***eiga*** (movie) and ***heiwa*** (peace). It has about 10,000 words, according to the fact that Japanese adults usually use 10,000 words in daily life [36].

Using the communication aid, a partner asks a patient to give the first three vowels (via the scheme described below) contained in the word that the patient wants to express. Then, the partner consults the dictionary by entering the three vowels and obtaining candidate words. When the partner cannot obtain appropriate candidate words, he or she either asks again for three vowels or replaces one vowel and again searches for candidate words. Once the candidate words are obtained, the partner confirms them according to whether the subject gives

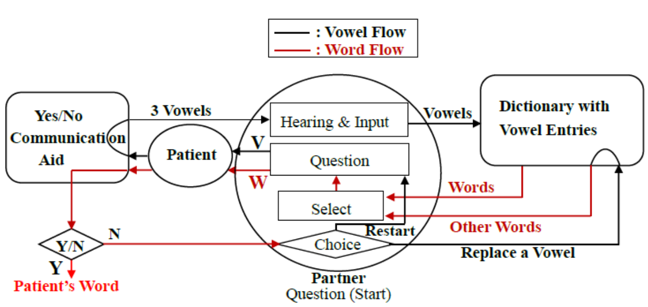
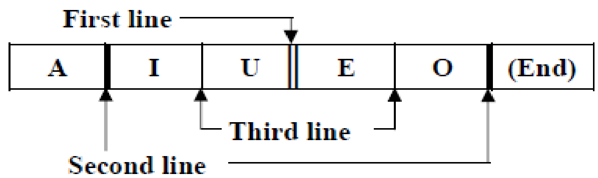


Fig. 1. Word communication system with partner assist. The partner plays three active roles: asking the patient for three vowels, selecting an appropriate word among the words that have those vowels and are returned by the dictionary, and checking several times whether the word is correct. The partner accepts the word if the patient confirms it enough times.



(a) Vowel division lines

A	I	U	E	O	(End)	NN
Y,Y	Y,N,Y	Y,N,N	N,Y,Y (N,Y)	N,Y,N (N,N)	N, N	N,Y,N

(b) Correspondence between vowels and "yes/no" answers

Fig. 2. Vowel table. (a) Vowel division lines. The lines divide the vowels into groups. The double line divides the vowels into {A, I, U}, {E, O, (End)}. The thick single lines divide the groups into {A}, {I, U} and {E, O}, {(End)}. Finally, the thin lines separate {I}, {U} and {E}, {O}. (b) Correspondence between vowels and sequences of "yes/no" answers. In the first vowel acquisition, because (End) can be excluded as the first choice, we assign "no, no" to O and "no, yes" to E. In the second or third vowel acquisition, when a patient answers "no, yes, no," it is assigned to the letter NN as well as O.

affirmative answers. When the subject does not give affirmative answers to any candidate words, the partner either stops or searches again for candidate words; on the other hand, when the subject gives affirmative answers to a candidate word, it is taken as the word expressed by the subject.

The scheme for determining a vowel works as follows. We use the dichotomic table shown in Fig. 2 (a). The patient is asked whether the vowel is in the left group and answers "yes" or "no" in a sequential way. For example, if the patient wants to select I, then he or she answers "yes" to the first question, "Does your word contain A, I or U?" (i.e., the group {A | I, U} is selected from {A, I, U ‖ E, O}). Then, the patient selects "no" (indicating the group {I | U}), and then "yes" (indicating {I}). Fig. 2 (b) summarizes the correspondence of the vowels to sequences of "yes/no" answers.

2) Confirmation of Expressed Words

To confirm that the finally selected word is the correct one, the partner uses the communication aid to ask the patient eight times whether the word is correct. For one word, a pair of questions is asked four times. The pair consists of an affirmative form, "Is it correct that your word is 'X'?", and a negative form, "Is it correct that your word is not 'X'?" When a patient answers "no" to the negative-form question, the patient's intention is regarded as affirmative.

For word confirmation, because the true word is unknown, we use Bayesian statistics. As we have no prior information on whether the selected word is correct or incorrect beforehand, we set the uniform prior probability density. Furthermore, because the communication aid's output is binary (i.e., affirmative or negative), we set, for a posterior probability density, the binominal likelihood with the affirmative rate, θ, and the negative rate, $1 - \theta$. The posterior affirmative probability, P, is given by integrating the posterior probability density over the range $0.5 < \theta \leq 1$. When seven answers are affirmative out of eight, the value of P is 0.980, and the partner regards the word as 98.0% credible. Similarly, when six answers are affirmative, the word is regarded as 91.0%

credible. In these cases, the partner accepts the word as the correct one. When five answers are affirmative, however, the value of P is 0.746 (74.6% credible). In that case, the Bayes factor BF helps with the decision: it is a measure indicating whether one hypothesis is more probable than another. In the present study, BF is the ratio of the posterior affirmative probability to the negative probability, i.e., $BF = P / (1 - P)$. For $P = 0.746$, $BF = 2.94$, which is almost equal to the boundary value of 3 that separates the ratings "Not worth more than a bare mention" and "Positive" [37]. In that case, the partner is free to decide acceptance.

C. Yes/No Communication Aid

1) Measurement

A patient is asked a question and changes his or her brain activity depending on whether the answer is "yes" or "no." The changes in activity are measured with near-infrared light as changes in the prefrontal blood volume. The present communication aid has two channels with one wavelength: it has two probes, one on the left forehead and one on the right forehead, and each probe has a light source (LED, 840-nm wavelength) and a Si PIN photodetector located 30 mm from the light source. The sampling frequency is 10 Hz. The change in the light intensity is converted to the change in the optical density $\Delta OD(t)$. Although the $\Delta OD(t)$ obtained at one wavelength contains contributions from both oxy- and deoxy-hemoglobin, the oxy-hemoglobin contribution dominates at 840-nm.

Each measurement consists of three periods of 12 seconds each: resting, answering, and resting again. The "yes/no" data is obtained by asking the subjects to either make their brain active or rest during the answering period. In the experiments reported here, the "yes" task was mental arithmetic or fast mental singing, and the "no" task was slow mental humming or imagining a landscape, which was the same task as in the resting periods.

2) Method of Yes/No Classification

The method of "yes/no" classification here is an extension of that described by Naito et al [25]. There are two major differences: one is that we use the variation in heart rate in addition to the hemoglobin concentration change in the cerebral cortex, and the other is the use of a support vector machine (L1 SVM with a Gaussian kernel) as the classifier. Although the heart rate and the cerebral blood volume vary in a similar manner, they can carry different information [38]. In the SVM, we set the cost parameter C to 1,000 and the kernel's variance σ^2 to 30.

The variation in blood volume accompanied by brain activity, $hb(t)$, and the heart rate, $hr(t)$, are obtained from $\Delta OD(t)$: $hb(t)$ is extracted by applying a low-pass filter with a cut-off frequency of 0.1 Hz to $\Delta OD(t)$ [25], while $hr(t)$ is obtained as follows. First, the pulse wave, whose frequency is typically 1 Hz, is extracted by using a band-pass filter to extract components in the range of $f_p \pm 0.3$ Hz, where f_p is the peak frequency searched in the range above 0.5 Hz. Second, the Hilbert transform [39] is applied to the pulse wave to obtain the unwrapped phase, $\varnothing_{pw}(t)$, from which the instantaneous heart rate $hr(t)$ is calculated as $hr(t) = (d\varnothing_{pw}(t) / dt) / 2\pi \times 60$ bpm. Finally, $hr(t)$ is smoothed by the low-pass filter. Waveform artifacts due to the Hilbert transform are removed at each end.

For the features characterizing the variations of $hb(t)$ and $hr(t)$, we use the amplitude and the degree of oscillation of $hb(t)$ and $hr(t)$ in a time window. We calculate these quantities by using an analytic signal derived from each wave of $hb(t)$ and $hr(t)$ in the time window [25]. The amplitude is the maximum instantaneous amplitude of the analytic signal, while the degree of oscillation is expressed by the rotation number [40], which we define in the present context as the increment in the unwrapped instantaneous phase in the time window divided by 2π. The amplitudes are rescaled so that their range has the same order of magnitude as that of the rotation numbers. The details are described in the Appendix.

The feature vectors input to the SVM are two-dimensional. We use three sets of features, from which the optimal one is to be selected: feature set 1 consists of the rotation numbers of $hb(t)$ and $hr(t)$, set 2 consists of the amplitude and rotation number of $hb(t)$, and set 3 consists of the amplitude and rotation number of $hr(t)$.

The accuracy of a classifier depends on the time window [25], [31], [41], [42], [43], [44], [45]. Because there are inter-individual variabilities in hemodynamic responses [46], we automatically optimize the time window [25], as well as the features [32] for an individual patient, in the process of training the SVM. The optimization procedure is described in the Appendix. In this way, feature set and time window are optimized for both the right and left forehead of each subject.

D. Experiments

1) Preliminary Experiments Using Labeled Questions

Before the word expression experiments, we performed two preliminary experiments, denoted hereafter as PE 1 and PE 2, for the purposes of training the subjects and partners and evaluating the performance of the proposed system. We used "yes/no" labeled questions whose answers were known. All experiments were done at the subjects' own homes. To avoid tiring the subjects, we limited the number of questions to as few as possible.

In PE 1, we evaluated to what extent the communication aid was effective for the recruited subjects. They received four days of training, once a week from April 7, 2018 to August 16, 2018. On each day, the SVM was trained with three pairs of "yes/no" training data and a pair of test data for cross-validation, as described in the Appendix. After the SVM training, partners asked the subjects to answer "yes" or "no" eight times (four times each), and the classification accuracy was calculated for each channel (i.e., the probe positions on the right or left forehead).

Then, PE 2 was conducted once a week from October 27, 2018 to February 13, 2019 for four weeks for each subject. In this preliminary experiment, we checked whether the subjects and partners were able to select correct vowels, and we trained them to use the word communication system. For these purposes, we asked the subjects and partners to use the system to select the first three vowels of the subjects' birthplaces, which the partners knew. Because the vowel selection was performed online, we had to determine suitable parameters to use. Accordingly, we performed a test experiment, which we call the “parameter test” hereafter, to select the channel and feature set that were expected to have a high~~er~~ classification accuracy. The results of PE 1 showed that the accuracy was not always good enough, as described later in Section III. *A*. It might be that the training data was too small or the brain activity changed after training the SVM. Therefore, we applied a procedure composed of steps (1) to (6) below. Our idea was to renew the training data by adding test data to it when necessary. The test data on which the classification accuracy was calculated consisted basically of four “yes/no” pairs as in PE 1, but we reduced the data to three pairs in some cases depending on the subject’s condition.

(1) Train the SVM as in PE 1 for both channels and all feature sets. Optimal time windows are set automatically.
(2) Check the accuracies of feature sets chosen as optimal by the optimization algorithm and select the channel giving higher accuracy (or both channels if their accuracies are the same).
(3) If the accuracy is at least 75%, go to step (6); otherwise, go to step (4).
(4) Check feature sets other than those chosen as optimal whether there are ones whose accuracy is at least 75%. If such feature sets exist, select ones giving the highest accuracy and go to step (6); otherwise, go to step (5).
(5) On the first run of this step, add the test data to the training data, retrain the SVM, and go to step (2). Otherwise finish parameter selection and stop.
(6) Adopt the selected channel and feature set. If multiple of them are selected, reduce them each to one by applying the following criteria successively: (a) the balance of “yes/no” answers to the test data, (b) the “yes/no” separation of the training data, and (c) the geometric margin.

When we retrain the SVM, it would be desirable to check the results by using new, independent test data. Obtaining additional new data is a burden, however, to ALS patients in the late stages, and we thus adopted the above procedure.

Following the above parameter test, the subjects chose the first three vowels of their birthplaces by using the vowel table. For example, when the first vowel of a subject’s birthplace was “A”, the first question to the subject was whether the vowel lay in (A, I, U) or not (E, O). Even when the subject answered incorrectly (E, O), the partner asked the second question to determine whether the first vowel was “A” or not (“I”, “U”), because the partner knew that the correct answer lay in (A, I, U). In this way, the subjects and partners learned how to use the word expression system, and we calculated the number of correctly selected vowels.

2) Word Expression Experiments (WH-Questions)

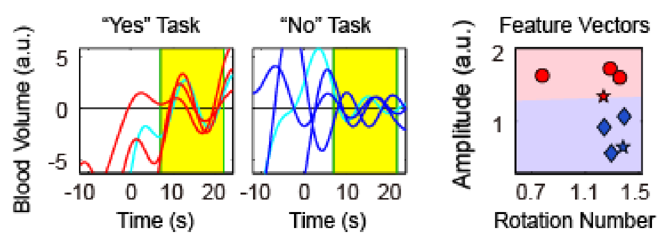
Word expression experiments were performed once a week from November 24, 2018 to June 7, 2019 at the subjects’ own homes. A member of a subject’s family chose themes and asked wh-questions, which could not be answered with “yes/no.” As described in Section II. *B. 1)*, the subject chose three vowels through the communication aid. The subject was then informed of the answer after each “yes/no” selection. The subjects were also instructed that, when they failed to give the correct “yes/no” answer, they were to just keep relaxing afterward in the vowel acquisition trial, because the correct vowel could not be obtained regardless of whatever “yes/no” response they had made. We also used the parameter test in the word expression experiments. In the parameter test, the number of test data sets ranged from two to four “yes/no” pairs, with three as the default number, depending on the subject’s condition. Accordingly, we lowered the threshold to 66.7 % (=2/3) in steps (3) and (4) when the SVM training data was original. For cases in which the test data was added to the training data, we kept the threshold at 75% because the classification accuracy should be high in those cases.

III. Results

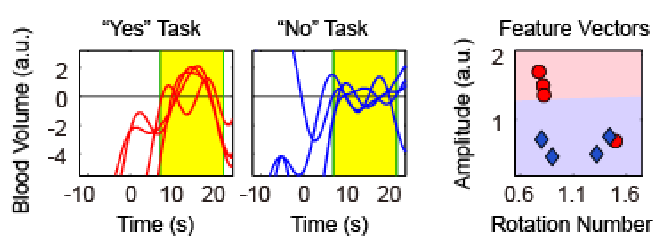
A. Preliminary Experiments

Fig. 3 shows an example of measured waveforms in PE 1, which were obtained from the left forehead of subject B on the first day. The optimization algorithm selected feature set 2 (the hemodynamic rotation number and amplitude) and a time window of 7-22 s. As seen in the figure, while only low-frequency Mayer waves were observed for the “no” task, task-related waveform variations were clearly seen for the “yes” task, except for one case in the test session shown in Fig. 3(b).

Table II lists the online classification accuracy in PE 1 for each channel (R: right forehead; L: left forehead). The feature set and time window selected as optimal are also listed. The listed average is the average of the higher accuracy rate of either the right or left forehead over four days. The confidence interval of the chance level was calculated as $p \pm \sqrt{p(1-p)/(n+4)}\, Z_{1-\alpha/2}$, where p = 0.5, $Z_{1-\alpha/2}$ is the $1-\alpha/2$



(a) Waveforms and feature vectors in an SVM training session



(b) Classification accuracy check using test data

Fig. 3. Examples of the oscillation of the blood volume *hb* around the baseline, and examples of the feature vectors, for the left forehead of subject B on the first day of the preliminary experiment 1. The yellow region represents the time window. The time origin, t = 0, is the starting point of the answering period. In the feature vector graphs, the pink regions represent “yes,” and the light purple regions represent “no.” (a) Waves and feature vectors in the SVM training session. The optimization algorithm selected feature set 2 (the hemodynamic rotation number and amplitude) and a time window of 7-22 s. The red and blue waves are the SVM training data, and the light blue waves are the data for cross-validation. The red (blue) marks represent the feature vectors for “yes” (“no”) answers. The stars represent vectors for cross-validation. (b) Results of the classification accuracy check for the decision function obtained in (a).

TABLE II
ONLINE YES/NO CLASSIFICATION ACCURACY OF PRELIMINARY EXPERIMENT 1

S‡	F†	Accuracy Rate				
		1st day	2nd day	3rd day	4th day	Average* ± SD
A	R	**75.0**	**75.0**	**62.5**	**50.0**	65.6 ± 12.0
	L	12.5	25.0	**62.5**	37.5	
B	R	37.5	62.5	50.0	**75.0**	78.1 ± 6.3
	L	**87.5**	**75.0**	**75.0**	**75.0**	
C	R	**62.5**	**50.0**	50.0	50.0	68.8 ± 16.1
	L	37.5	37.5	**75.0**	**87.5**	
D	R	**75.0**	**62.5**	50.0	37.5	62.5 ± 10.2
	L	62.5	12.5	**62.5**	**50.0**	
E	R	**50.0**	**75.0**	**75.0**	**62.5**	65.6 ± 12.0
	L	37.5	50.0	62.5	50.0	
		Total Average ± SD				68.1 ± 11.8

S‡: Subject, F†: Side of forehead (Right or Left).
*: The average is that of the higher accuracy rate (bold letters) of either the right (R) or left (L) forehead on each day.

TABLE III
NUMBER OF CORRECT VOWELS OBTAINED ONLINE IN PRELIMINARY EXPERIMENT 2

S‡	V‡	Number of correct vowels (accuracy rate*, forehead, feature set)			
		1st day	2nd day	3rd day	4th day
A	A, I, A	**3** (75.0, R, 3)	**2** (100, L, 2)	0 (75.0, R, 2)	1 (100, R, 2)†
B	O, U, I	0 (87.5, R,2)†	**2** (75.0, L,1)†	1 (75.0, R, 3)	0 (87.5, R, 2)
C	A, A,A	0 (100, R, 3)†	**2** (87.5, R,3)†	1 (87.5, L,3)†	0 (87.5, R,1)†
D	I, A, A	**2** (75.0, R, 1)	0 (75.0, L, 1)	0 (83.3, R, 1)	0 (83.3, R,1)†
E	U, U, I	0 (75.0, L, 1)	0 (100, L, 3)†	0 (100, R, 3)†	**2** (83.3, R, 2)†

S‡: Subject, V‡: First three vowels in birthplace.
*: "Yes/no" classification accuracy of the parameter test.
†: Parameter test data was added to the original training data for training the SVM.

quantile of the normal distribution, and α is the significance [47]. When we set $\alpha = 0.1$, the interval was 26.3-73.7%. For subject B, the classification accuracy on the left forehead significantly exceeded the chance level throughout the experiments. For the other subjects, however, there were days when the accuracy did not significantly exceed the chance level even for the better channel. However, the fact that the null hypothesis of randomness is not rejected does not necessarily mean that the accuracy is definitely random. We thus proceeded to PE 2 according to steps (1) to (6) given in Section II. *D. 1)*.

In PE 2, the first three vowels of the patients' birthplaces were (A, I, A) for subject A, (O, U, I) for subject B, (A, A, A) for subject C, (I, A, A) for subject D, and (U, U, I) for subject E. The corresponding sequences of "yes/no" answers were (yes, yes | yes, no, yes | yes, yes) for subject A, (no, no | yes, no, no | yes, no, yes) for B, (yes, yes | yes, yes | yes, yes) for C, (yes, no, yes | yes, yes | yes, yes) for D, and (yes, no, no | yes, no, no | yes, no, yes) for E.

Table III lists the numbers of correctly selected vowels. Cases listed without the symbol † were obtained with the original SVM training data, while cases with † were obtained by adding the test data to the original training data, as noted in step (5) above. To obtain a correct word in the present system, it is desirable that at least two correct vowels are selected. If a subject selects three vowels correctly, his or her partner should easily find the correct word in the dictionary. If two vowels are correct, the partner should be able to guess and replace a vowel during the communication process. With only one correct vowel, however, it is probably impossible to obtain the correct word. As listed in Table III, subject A gave three correct vowels once and two vowels once. All subjects other than E gave two or three vowels correctly within two sessions. As a result, we expected that the subjects and partners would be able to obtain the subjects' words within three or four sessions, and we proceeded to the word expression experiment.

B. *Expressed Words for Wh-Questions*

Table IV lists the words that the subjects expressed. Column 2 lists the session numbers in which each subject selected three or two correct vowels. The column also lists the total number of sessions including word confirmation, in parentheses. It was

TABLE IV
EXPRESSED WORD OF EACH SUBJECT

S+	Session* (Total No) **	Accuracy*** (Parameters) †	Wh-question	3 vowels	Expressed word	C+
A	Third (5)	100 (Original, L, 3, 2-17)	Favorite animal	E, A, A	*Medaka* (killifish)	91.0 %
B	First (3)	75.0 (Original, R, 3, 0-21)	Comment on system	U, A, O (NN)	*Fuanntei* (unstable)	81.3
C	Third (4)	66.7 (Original, R, 3, 0-22)	Favorite genre for reading	E, I, A → E, I, I	*Rekishi* (history)	74.6
D	Second (3)	83.3 (Addition, R, 3, 5-21)	‡Trans-potation method to return to hometown	O, O, U → I,O,U	*Hikouki* (airplane)	91.0
E	Third (4)	66.7 (Original, L, 3, 1-21)	Comment on system	A, I, A	*Arigatai* (thanks)	74.6

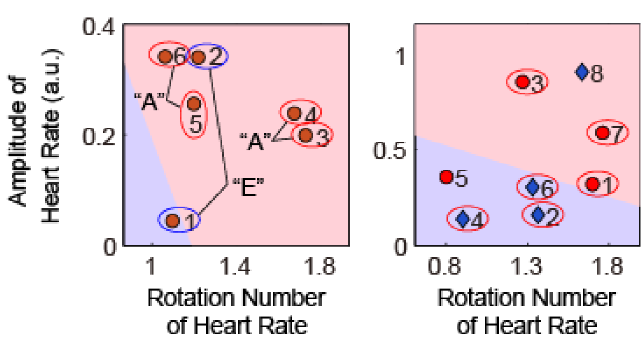
S+: Subjects, C+: Credibility.
*: Session at which the subject selected more than one correct vowels which led to his or her word (one session per day).
**: (Total number of sessions including confirmation of words).
***: Accuracy rate of the parameter test at the day where subject selected vowels which led to correct word.
†: (SVM Training data, Side of Forehead, Feature set, Time window), Original: Original training data, Addition: Original + Parameter test data, R: Right, L: Left.
‡: The partner was convinced that "***Hikouki***" was the only suitable method but didn't lead the subject toward it.

difficult to confirm a word in the same session when the word was obtained, because the time of one experimental session was limited to 30 minutes by the Institutional Review Board. For subject A, who selected two or three correct vowels twice in PE 2, the credibility of the expressed word was high. Subject B, whose average online "yes/no" classification accuracy exceeded the chance level in PE 1, selected three correct vowels in the first session. The word credibility was also high for subject D, who selected two correct vowels on the first day in PE 2. Column 3 lists the "yes/no" classification accuracy of the parameter test when the subjects selected vowels that led to the correct word. Feature set 3 was selected as optimal for all the subjects. In the following, we describe the detailed experimental results for each subject.

1) *Subject A*

The theme "favorite animal" was given by the subject's wife, who anticipated the answer "dog" or "cat." His expressed word, however, was *medaka* (killifish), which none of his partners (i.e., his wife, an occupational therapist, and a nursing-care helper) expected. He took five days to express that word. It was confirmed by his affirmative answers six times out of eight.

On the first day, subject A answered all "no" for the three vowels, which resulted in "O, O, (End)." Unfortunately, there were no appropriate candidate words in the dictionary. On the second day, his partners chose ***hato*** (pigeon), ***neko*** (cat), ***hito*** (person), and "other" among 14 candidate animals in which one vowel differed from "O, O." His wife asked him words that were divided into two groups of (1) *hato* or *neko* and (2) *hito* or "other." His answer was in group (1) three times out of four. Then, his wife was sure that his answer was *neko* and asked him if it was correct. He replied that it was three times out of four. She asked again about groups (1) and (2) and he answered "no" for both. As a result, the partners were at a loss and finished up for the day.



(a) Vowel acquisition (b) Word confirmation

Fig. 4. Feature vectors for subject A. (a) Vectors in vowel acquisition when the vowel sequence "E, A, A" was obtained from the left forehead. The "yes/no" classification algorithm selected feature set 3 (the rotation number and amplitude of the heart rate *hr*) and a time window of 2-17 s as optimal. (b) Vectors in word confirmation from the right forehead. The red circles represent "yes" answers to the affirmative question, while the blue diamonds represent "no" answers to the negative question. Thus, the red circles in the "yes" region (1, 3, 7) and the blue diamonds in the "no" region (2, 4, 6) are regarded as affirmative. The classification algorithm also selected feature set 3 in the confirmation session, but with a time window of 4-23 s.

On the third day, the partners started from the beginning and asked subject A for three vowels. This time, he expressed "E, A, A," as shown in Fig. 4(a), for which there was one candidate word: ***medaka***. The partners tried to confirm it, and he answered "yes" only two times out of four, so they could not decide his word. On the fourth day, he expressed "E, A, E." Though the partners found no candidate words in the dictionary, they noticed that "E, A, E" differed by just one vowel from the previously expressed vowels "E, A, A." They asked him if "E, A, A" was correct, and his answer was "yes." Then, they asked if *medaka* was correct, to which he answered "yes" two times. At this point it seemed probably correct. Finally, on the fifth day, the partners asked subject A if *medaka* was correct, and he answered affirmatively six times out of eight, as shown in Fig. 4(b).

2) *Subject B*

The wh-question, "How do you like the word communication system?", was given by the subject's aunt, and his answer was *fuanntei* (unstable). On the first day, he expressed "U, A, O," and she selected ***fumann*** (dissatisfaction) and ***fuann*** (uneasiness). He answered "no" to *fumann* and "yes" to *fuann*. On the second day, she asked whether "U, A, O" was correct, and he answered "yes" three times out of four. Then, she added ***fuanntei*** to the candidate words, because she thought it was more suitable for her question than *fuann*. She thus gave him a fourfold choice of *fumann*, *fuann*, *fuanntei*, and "other," which actually resulted in *fuanntei*. She then confirmed it twice, and he answered that it was correct twice. Finally, on the third day, the aunt confirmed it again, and subject B answered that it was correct three times out of four, giving a posterior affirmative probability P of 0.814 and a BF of 4.38 (rating "Positive"). At that point, she accepted the word. The word "unstable" probably came from his experience two years before the present experiment: he had used the communication aid on a trial basis for two weeks, but the accuracy rate was unstable then.

3) *Subject C*

The wh-question, "What is your favorite genre for reading?", was given by the subject's mother. He expressed *rekishi* (history). He used to like listening to his partners (his mother and his caregivers) read books on Roman history, philosophy, and ethics. She thought his taste might have changed and thus asked this question.

On the first day, subject C expressed "I, E, O," and his mother selected *shizenn* (nature) among 48 candidate words. He denied that word, however, by giving a "no" answer. On the second day, she started from the beginning, and he expressed "O, A, (End)." Just to make sure, she looked up "O, A, (End)" in the dictionary and found *rohma* (Rome) as a candidate word. She asked him if *rohma* was correct, and he denied it twice. On the third day, *rohma* was asked again, because he used to like Roman history. He answered "no," however, six times out of eight. Therefore, she started fresh from the beginning, and he expressed "E, I, A." She guessed ***eiga*** (movie) among the candidate words and asked him if it was correct, but it was not.

Then, after the third day, the subject's mother noticed that "E, I, A" became "E, I, I" if the last vowel A was replaced with I, which suggested *rekishi*. Finally, on the fourth day, she asked him if *rekishi* was correct, and he answered affirmatively five times out of eight.

4) Subject D

The wh-question, "What transportation method do you like to use to return to your hometown?", was given by the subject's son. She expressed *hikouki* (airplane). Her hometown is far from Tokyo, where she lives, and her son said that air transport was actually the only suitable method among road, rail, air, and sea transport, because the other methods take too much time for her to return to her hometown.

On the first day, Subject D expressed "I, I, I," but her son found no appropriate words in the dictionary. On the second day, she expressed "O, O, U." He then found the appropriate words *hikouki* and *jidousha* (automobile) in the dictionary by replacing the first O with I. On the third day, he asked whether *hikouki* or *jidousha* was correct, and she confirmed *hikouki* six times out of eight.

5) Subject E

The wh-question, "How do you like the word communication system?", was given by the subject's wife and daughter. On the first day, he expressed "U, A, I." His daughter found 72 candidate words in the dictionary, but none of them were appropriate. On the second day, his daughter sought to confirm "U, A, I," and he answered "no" three times out of four. Then, she started from the beginning and obtained the three vowels "O, U, (End)." She found 98 candidate words in the dictionary but again none were appropriate.

Then, on the third day, Subject E expressed "A, I, A," and his daughter found 219 words in the dictionary. Among those words, she selected *arigatai* (thanks) and confirmed it with him. He answered "yes" two times and "no" two times, unfortunately. Finally, on the fourth day she asked again whether it was correct, and this time, he answered affirmatively five times out of eight.

IV. Discussion

In this paper, we have proposed a simple word communication system for daily home use by ALS patients in a severely locked-in state. In this system, partners are actively involved in obtaining words that patients want to express. Here, the process of word expression itself becomes a kind of conversation between patients and partners, which is expected to improve patients' quality of life. Käthner et al. [48] suggested that direct interaction between a patient and an interlocutor raised the patient's preference for partner-dependent assistive devices.

To reach a patient's true word, partner intervention is essential because only subject B expressed three vowels correctly in the first session, whereas the other subjects failed to do so. In those cases, the partners had to change one vowel or start over. Subject A's partner (his wife) succeeded by replacing one vowel, because she noticed that he gave almost the same vowels (E, A, A) and (E, A, E). Subject C's partner (his mother) also succeeded by replacing one vowel (A) with I, which changed (E, I, A) to (E, I, I). Subject D's partner (her son) was convinced of the correct answer and the first three vowels. Therefore, he did not have to replace a vowel and simply started afresh on the second day, and the subject selected two correct vowels. Finally, subject E's partner (his daughter) was successful when she started over again.

The partners' heuristic capability was especially helpful. For example, subject A's wife asked her husband, "What do you hate most?", one day after the experiment had finished. He answered "E, E, E," but there were no appropriate candidate words (among only two candidates: *Eberesuto* (Everest) and *erebehtah* (elevator)). She immediately understood, however, that the correct word was "ALS," because its pronunciation in Japanese is "*ei* (A), *eru* (L), *esu* (S)," though the first three vowels are "E, I, E (*eieruesu*)." When she confirmed "ALS," he showed affirmative intention seven times out of eight. This is a typical case in which the heuristic capability is helpful.

While subjects B and E could not select three correct vowels in PE 2 (Table III), they succeeded in the word expression experiment with wh-questions (Table IV). It may be that, because the wh-questions concerned the patients' real lives, they had increased motivation to respond.

For a BCI communication system to be used at a patient's home, it must be simple to use: it must be usable without technical support, the setups of the apparatus and the decision function need to finish within a short time. The system must also be inexpensive. The system reported here fulfills all of these requirements. A patient only needs a half-cut plastic band with a pair of probes on his or her forehead, and software installed in a PC measures the hemodynamics, calculates feature vectors, trains the SVM, and optimizes the feature set and time window. No professional technical support is necessary, and patients do no need training to use an fNIRS-based BCI.

At present, the system has several limitations, which are basically due to the communication aid. It took 3-5 days for the subjects to express their words (with a 30-minute session each day). We will need to improve the online classification accuracy of the "yes/no" communication aid in order to reduce the time needed for patients to express words. Although the classification accuracy of BCIs is high for healthy people [18], [19], it is generally low for heavily locked-in patients. The low accuracy might suggest that the number of questions asked in training the classifier should be kept as small as possible to avoid tiring patients. To raise the classification accuracy, one possible approach would be to add past data to the training data and thus increase the available data for training the classifier. Selection of the feature set and time window in reference to a patient's past tendencies is another possibility. For example, with the present communication aid, there were cases when we obtained good parameters by using the moving average of the accuracies of past tests. Application of deep learning methods is another possible approach [49], [50].

The best combination of the channel, feature set, and time window differed on every day of measurement even for the same patient, and we had to optimize the parameters every time. To improve the system's usability, it would be desirable for partners to use the same parameters at least several times, even though the physical conditions and motivations of patients are not constant. In this context, there were cases when we obtained good results by choosing the best-suited decision function from past ones. The usability could also be improved by using feature sets that are relatively insensitive to patients' conditions. From the viewpoint of usability, training and personalization of the dictionary would help partners find appropriate words. Studies on finding easy, stress-free tasks would also help patients to answer "yes" with ease.

The structure of English is different from that of Japanese, but our method is also applicable to an alphabet letter matrix. One such possible matrix consists of six rows and six columns. The alphabet letters are grouped according to column numbers: column 1 (A, F, K, P, U, Z), column 2 (B, G, L, Q, V), column 3 (C, H, M, R, W), column 4 (D, I, N, S, X), column 5 (E, J, O, T, Y), and column 6 (space). For example, if a patient chooses the three column numbers, "4, 1, 5," then the candidate words are the following: "data," "date,"…,"suede," "suet" (131 words) [51]. If the partner asks the patient, "What genre would you like to listen to?", then the answer "4, 1, 5" could mean "sports": S in column 4, P in column 1, and O in column 5.

BCIs based on fNIRS [25], [27], [31], [32] and EEG [28], [29], [30] enable CLIS-ALS patients to answer "yes/no" to questions. By using these BCIs as communication aids, a system in which patients and partners cooperate as proposed in this study will enable ALS patients in CLIS or almost in CLIS to communicate beyond binary "yes/no" responses.

Appendix

The feature vectors are obtained as follows. Given a time window, we make a baseline by applying the least-squares method to the wave data in the window; then, we subtract the baseline from the wave to obtain the oscillation around the baseline. We then apply the Hilbert transform to the oscillating wave and obtain the instantaneous amplitude $A(t)$ and the unwrapped instantaneous phase $\phi(t)$. At both ends of the analytic signal, we discard data over 1 s to remove transform-induced waveform artifacts near the end regions. The rotation number is given by $R = \{\phi(t_f) - \phi(t_i)\}/2\pi$, where $t_i = t_s + 1$ and $t_f = t_e - 1$ for the time window $t_s \leq t \leq t_e$ (s), and the amplitude is given by $Amp = \max\{A(t_i \leq t \leq t_f)\}$.

The feature set and time window are automatically optimized during SVM training. We train the SVM with several pairs of "yes/no" training data and a pair of test data for cross-validation. First, we train the SVM scanning the time window for a given feature set. In this process, we check a performance measure, defined as the average of the separation of training vectors and the classification accuracy of cross-test vectors, and select the time window(s) with the largest measure. When there are multiple selected windows, the one giving the largest geometric margin in the SVM is adopted. For the searched time windows, the starting point increases every second, starting from 0 s, which is the starting point of the answering period, and the width increases by 1 s for each starting point, starting from a width of 15 s. Because we found that $hb(t)$ lags $hr(t)$ by 3 s on average for the "yes" task, which should represent the delay of the hemodynamic response, we shift the time window for $hb(t)$ back by 3 s in feature set 1. In this way, the time window is determined for each feature set. Next, the optimal feature set is selected by using the above performance measure and the geometric margin.

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