Comparison of Mixed phase and frequency coded SSVEP and c-VEP BCI

Jun-ichi Sato

October, 28, 2016

Index

- Review of last seminar
- Mixed coded SSVEP
- Preliminary Experiment
  - Results
- Experiment
  - mixed-coded SSVEP VS c-VEP
  - Results
- Proposed method : optimized combine method
- Conclusion and future works
  - Online Experiment

Review of last seminar

- **Mixed phase and frequency coded SSVEP** was proposed in 2014
- It improves the performance of SSVEP BCI
- I did the further experiment,
  frequency detection was succeed, phase detection was failed
  - 32 Targets accuracy : about 20 % (chance level : 3.1 %)
  - Only frequency : about 60 % (chance level : 12.5 %)
  - Only Phase : about 30 % (chance level : 25 %)

- I considered the reasons
  1. The number of training samples were not enough
  2. The channel positions were not optimized for visual stimuli
     - The paper : F3, FZ, F4, CZ, P1, PZ, P2, PO3, POZ, PO4, PO3, O1, OZ, O2, PO8, CPZ
     - My old study : P1, PZ, P2, PO3, POZ, PO4, PO7, O1, OZ, O2, PO8, PO9, O9, IZ, O10, PO10
  3. The images were not checker-board images
  4. The measurement time was too short (single trial : 4 sec)

Mixed frequency and phase coded SSVEP

- SSVEP problems
  - restricted the number of targets by display refresh rate
  - It has been reported lower ITR compared to c-VEP [1]
- Mixed frequency and phase coded SSVEP [2]
  - 32 targets (8 frequency x 4 phase)
  - Classification method was ensemble of CCA spatial filter
    - It needs training data for phase detection
  - exhibited 166 bits/min
    - It broke the previous record (c-VEP) 144 bits/min
- The paper [2] was not compared ITR with mixed SSVEP and c-VEP in same experimental condition.
  It just compared with the results of papers

[1] G. Bin, X. Gao, Y. Wang, B. Hong, and S. Gao. VEP-based brain- computer interfaces: time, frequency, and code modulations [research frontier]. *Computational Intelligence Magazine, IEEE*, 4(4):22–26, 2009.

[2] A high-speed brain speller using steady-state visual evoked potentials,

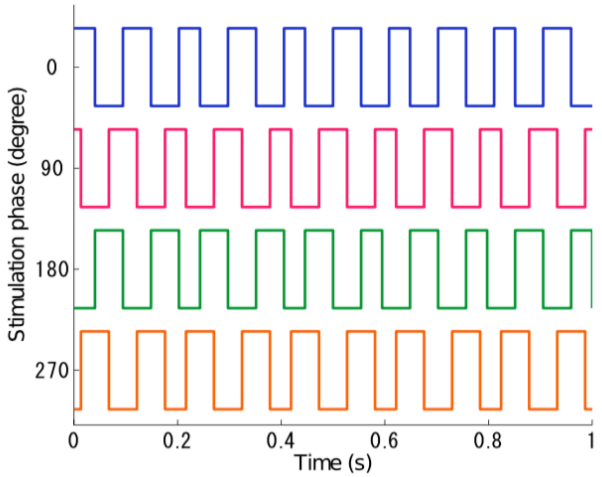
M. Nakanishi, *International journal of neural systems,* Vol. 24 Issue 06, 2014

Mixed Coded SSVEP : Visual Stimuli

- To generate any frequency of visual stimuli, approximate approach [3] was proposed
- Visual stimuli of mixed coded SSVEP is given by

$$S(f, \phi, i) = \text{square}\left[2\pi f\left(\frac{i}{\text{RefreshRate}}\right) + \phi\right]$$

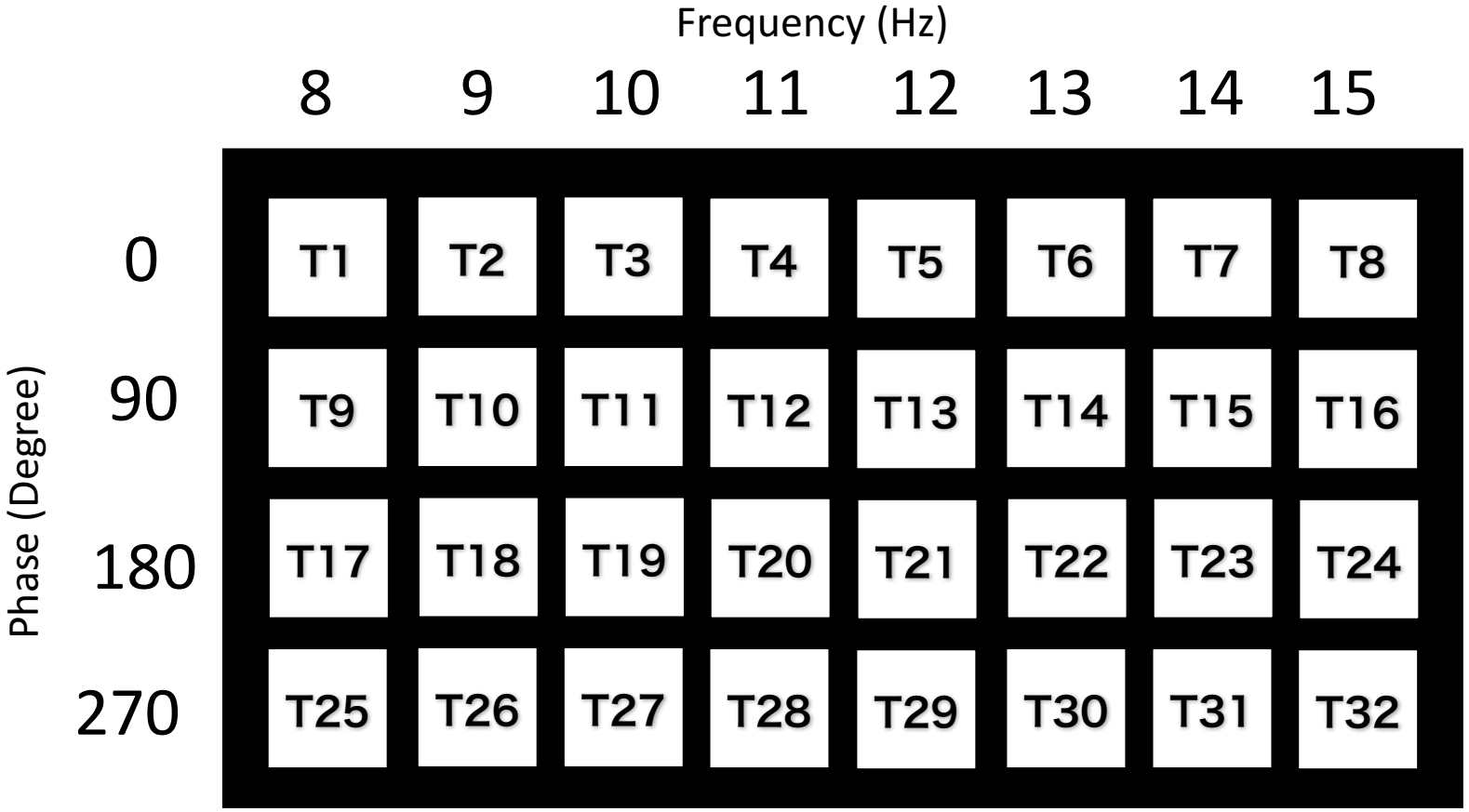
  - f : Frequency of visual stimuli
  - i : frame index
  - ϕ : initial phase
  - square[] : generates square wave ([0, 1])
- In the paper, initial phases 0, 90, 180, 270 were used



[3] Y. Wang, Y. T. Wang and T. P. Jung, Visual stimulus design for high-rate SSVEP BCI, Electron. Lett. 46(15) (2010) 1057-1058.

Mixed Coded SSVEP : Targets alignment

- 32 targets were aligned like below figure



Normal SSVEP Classification

Canonical Correlation Analysis (CCA) for SSVEP

- $\boldsymbol{X}$: EEG matrix (row : electrodes, columns : times)
- $\boldsymbol{Y}$: reference signals

$$\boldsymbol{Y}_f = \begin{bmatrix} \sin(2\pi f n) \\ \cos(2\pi f n) \\ \vdots \\ sin(2\pi N_h f n) \\ cos(2\pi N_h f n) \end{bmatrix}, \qquad n = \frac{1}{f_s}, \frac{2}{f_s}, \dots, \qquad \frac{N}{f_s}$$

  - f : target frequency
  - f_s : sampling frequency
  - N_h **:** number of harmonics frequencies

- The weight of spatial filter is given by

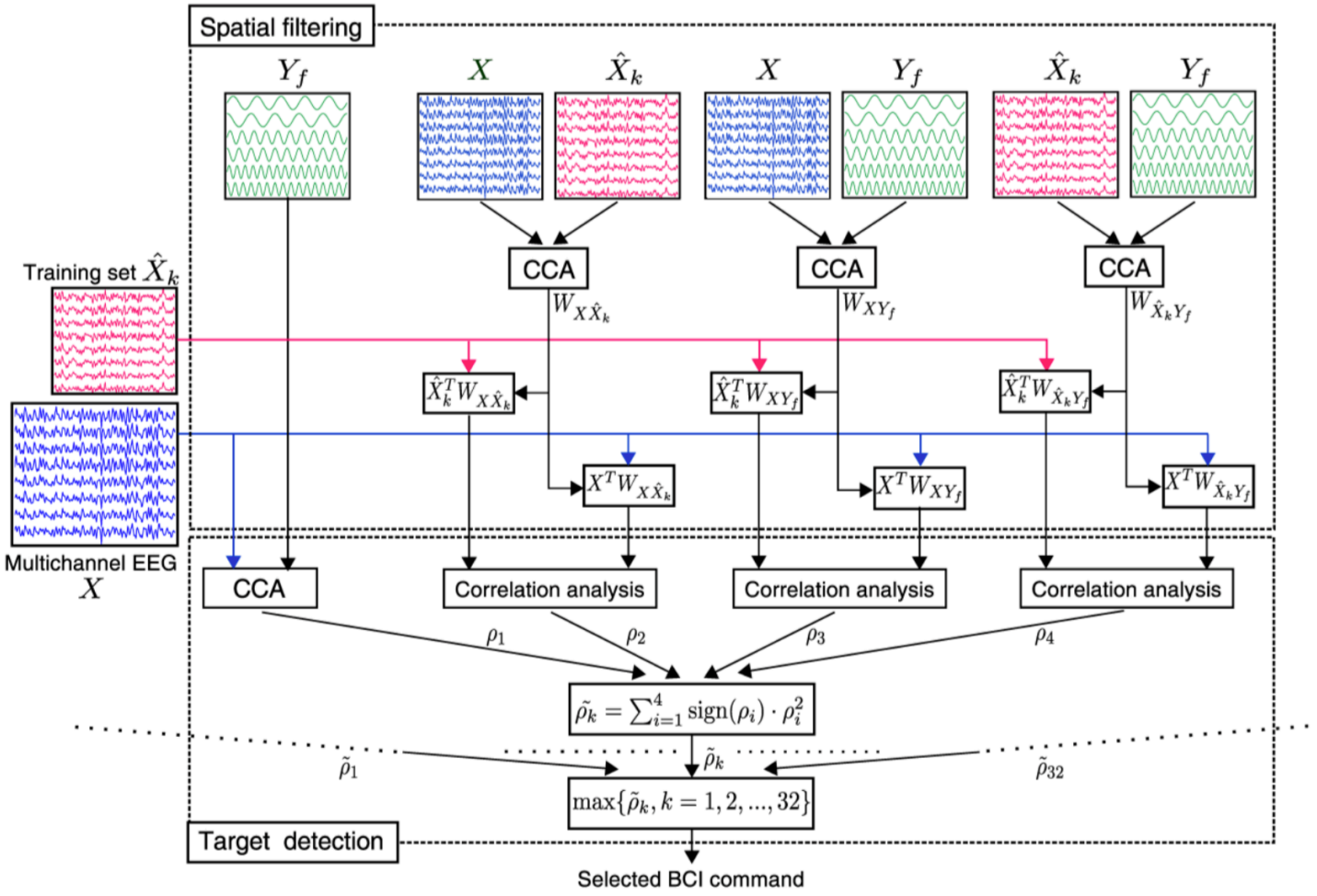
$$\max_{\boldsymbol{w}_{X_f}, \boldsymbol{w}_{Y_f}} \rho_f = \frac{\boldsymbol{w}_X^T \boldsymbol{X} \boldsymbol{Y}_f^T \boldsymbol{w}_Y}{\sqrt{\boldsymbol{w}_X^T \boldsymbol{X} \boldsymbol{X}^T \boldsymbol{w}_X} \sqrt{\boldsymbol{w}_Y^T \boldsymbol{Y}_f \boldsymbol{Y}_f^T \boldsymbol{w}_Y}}$$

- Correlation coefficient ρ is used for detecting a command

$$f^* = \underset{f}{\operatorname{argmax}} \rho_f$$

Mixed Coded SSVEP : Classification (1)

- To detect the phase, averaging EEG $\widehat{\boldsymbol{X}}_k$ ($k = 1, \ldots, 32$, target number) are used



Mixed Coded SSVEP : Classification (2)

$$\boldsymbol{\rho} = \begin{bmatrix} \rho_1 \\ \rho_2 \\ \rho_3 \\ \rho_4 \end{bmatrix} = \begin{bmatrix} \rho(\boldsymbol{X}^T \boldsymbol{w}_{XY} \boldsymbol{Y}_f^T \boldsymbol{w}_{XY}) \\ \rho(\boldsymbol{X}^T \boldsymbol{w}_{X\hat{X}}, \hat{\boldsymbol{X}}^T \boldsymbol{w}_{X\hat{X}}) \\ \rho(\boldsymbol{X}^T \boldsymbol{w}_{XY}, \hat{\boldsymbol{X}}^T \boldsymbol{w}_{XY}) \\ \rho(\boldsymbol{X}^T \boldsymbol{w}_{\hat{X}Y}, \hat{\boldsymbol{X}}^T \boldsymbol{w}_{\hat{X}Y}) \end{bmatrix}$$

- M1 : ρ_1, Normal SSVEP Classification
- M2 : ρ_2, Spatial filter between test and training
- M3 : ρ_3, Spatial filter between test and sin-cos reference
- M4 : ρ_4, Spatial filter between training and sin-cos reference
- M5 : $\tilde{\rho}$, combined decision,

$$\tilde{\rho} = \sum_{i=1}^{4} \text{sign}(\rho_i) \cdot \rho_i^2$$

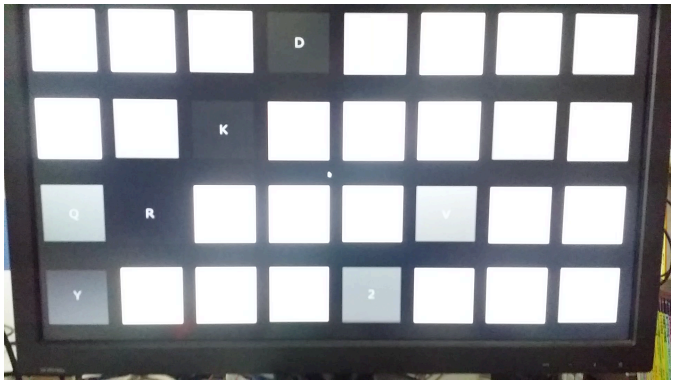
Reduction of calculation cost

- In M1 and M4, same spatial filter was used
- $\boldsymbol{Y}_f = \boldsymbol{Y}_{\text{mod}(k-1,\,8)+8} \quad (k = 1, \ldots, 32)$

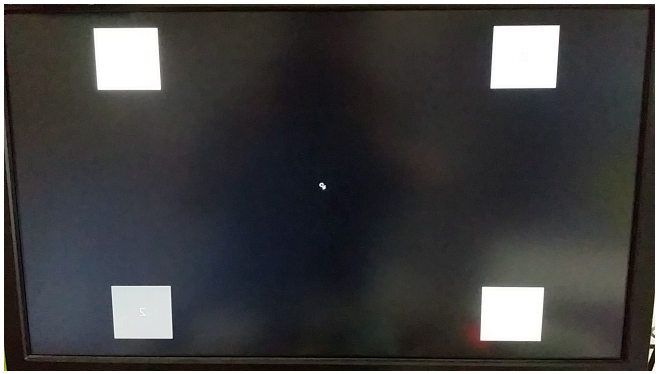
Preliminary experiments

- I did five experiments to investigate why phase detection was failed
- The electrodes were positioned at
  - P1, PZ, P2, PO3, POZ, PO4, PO7, O1, OZ, O2, PO8, PO9, O9, IZ, O10, PO10

1. 4 commands SSVEP (32 targets remain)
   - Increasing the training samples (40 samples)
2. 4 command SSVEP (Displayed 4 targets, same frequency)
   - Increasing the training samples (40 samples)
   - Eliminate the effect of other targets



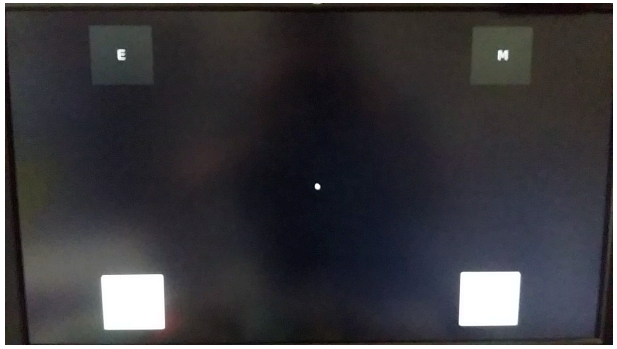
ex. 1



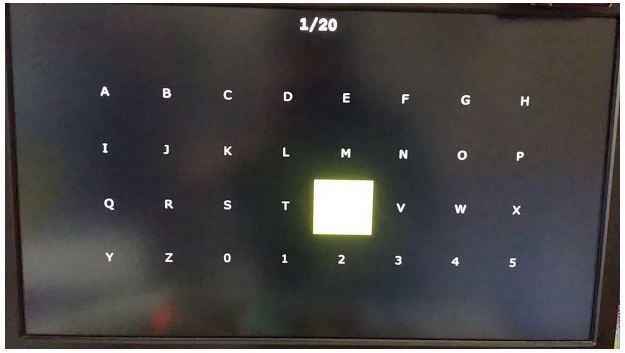
ex. 2

Preliminary experiments

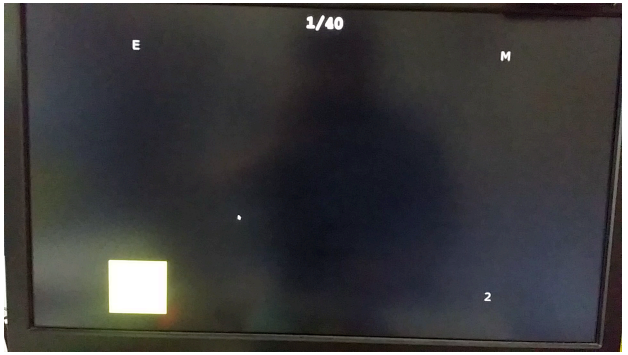
3. 4 commands c-VEP
   - almost same as ex. 2, stimuli was replaced m-sequences
4. 32 commands c-VEP
   - my old experiment
5. 4 commands SSVEP (Displayed 4 targets, same frequency), each measurement is divided



ex. 3



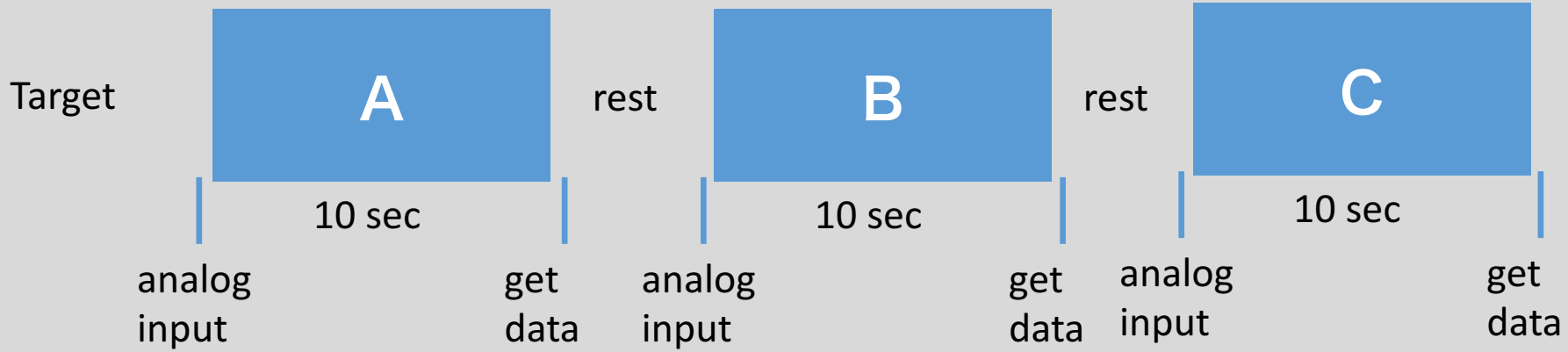
ex. 4



ex. 5

Measurement

Measurement is divided



Measurement is not divided

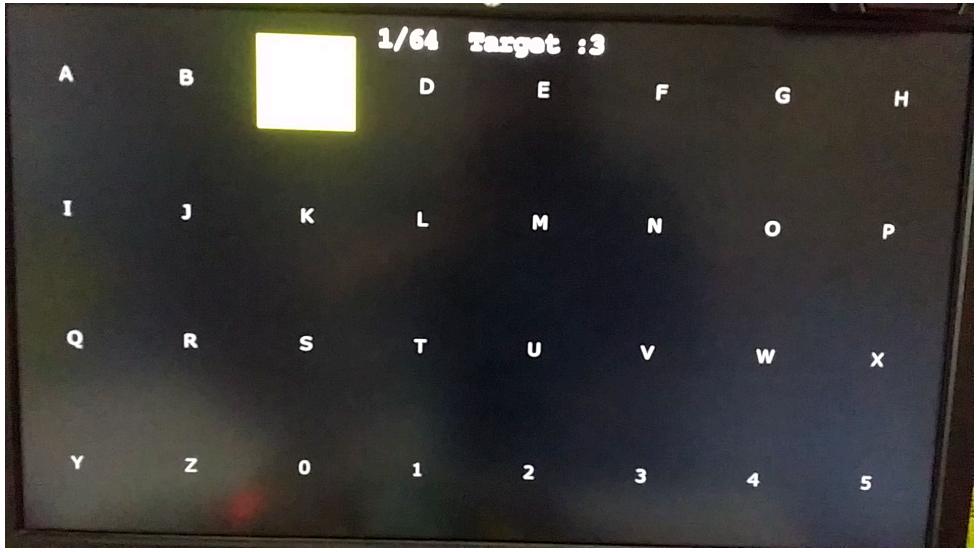
Preliminary experiments : Results and Discussions

- ex. 1 and ex. 2 was failed
  → the number of trainings is the reasons
- The classification of four command c-VEP (ex. 3) was failed
- However, old c-VEP experiment (ex. 4) was succeeded
- **whether measurement is divided or not is the factor**
- When measurement time is long, it may become unstable

	type	commands	measurement was divided	Accuracy
ex. 1	SSVEP	4	false	0.35
ex. 2	SSVEP	4	false	0.30
ex. 3	c-VEP	4	false	0.26
ex. 4	c-VEP	32	true	0.94
ex. 5	SSVEP	4	true	0.95

Experiment : mixed-coded SSVEP VS c-VEP

- I compared mixed-coded SSVEP with c-VEP at same experimental condition
- SSVEP or c-VEP stimuli is randomly displayed
- One run : 64 targets (SSVEP:32, c-VEP:32)
- Six runs were carried out (6 x 32 = 192 targets)
- Single target was recorded for 4 seconds
  - It recorded 5 seconds,
    first 0.5 sec and last 0.5 sec were removed after filtered
- Beginning of each trial, yellow rectangle appeared



c-VEP : classification

CCA spatial filter

- $\boldsymbol{X}_k$: k trial training EEG matrix
- $\boldsymbol{R} = \frac{1}{K}\sum_{k=1}^{K} \boldsymbol{X}_k$

$$\max_{\boldsymbol{w}_X, \boldsymbol{w}_R} \frac{\boldsymbol{w}_X^T \boldsymbol{X}\boldsymbol{R}^T \boldsymbol{w}_R}{\sqrt{\boldsymbol{w}_X^T \boldsymbol{X}\boldsymbol{X}^T \boldsymbol{w}_X}\sqrt{\boldsymbol{w}_R^T \boldsymbol{R}\boldsymbol{R}^T \boldsymbol{w}_R}}$$

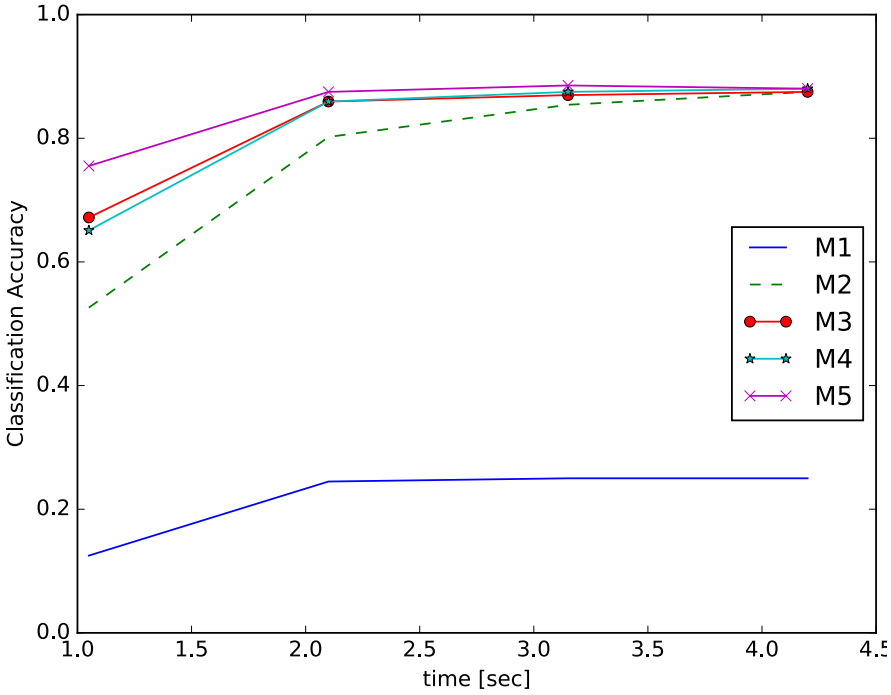
Template matching

- In conventional c-VEP research, templates were generated by circular shifting of averaged signal
- In this experiment, training and testing was not separated.
  Template $T_k[t]$ is generated by averaged signal of target k **without circular shifting**
- The target is estimated by

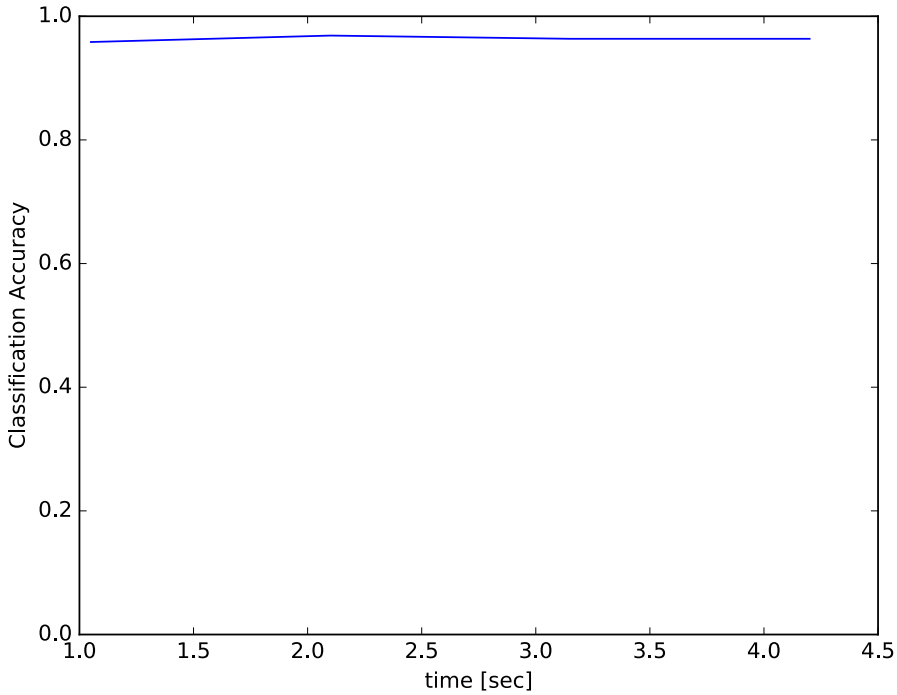
$$\underset{k}{\operatorname{argmax}} \frac{\sum_{t=0}^{T-1} T_k[t]x[t]}{\sqrt{\sum_{t=0}^{T-1} T_k^2[t]}\sqrt{\sum_{t=0}^{T-1} x^2[t]}}$$

mixed coded SSVEP vs c-VEP : Accuracy

- Leave one out : (the number of samples was 192)
- mixed coded SSVEP : 0.8802
- c-VEP : **0.9635**
- c-VEP was obviously better than mixed coded SSVEP



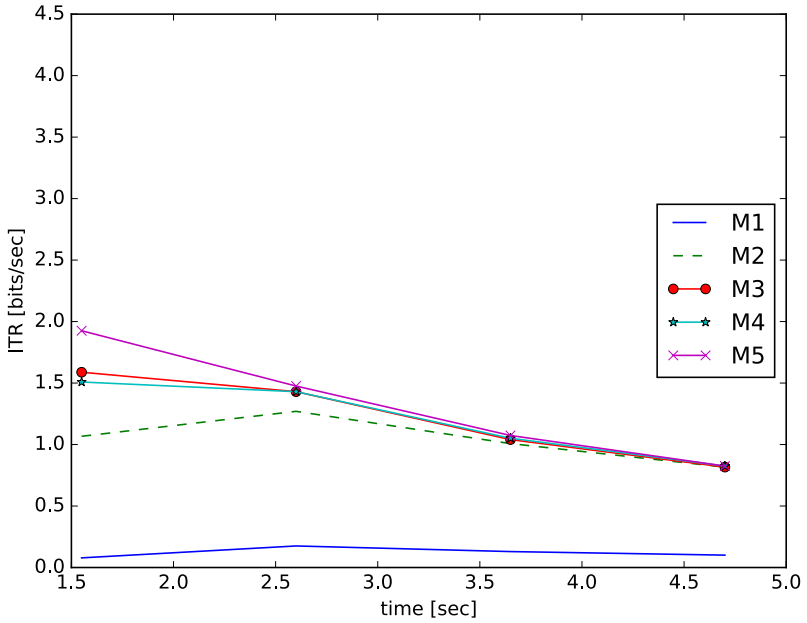
mixed coded SSVEP



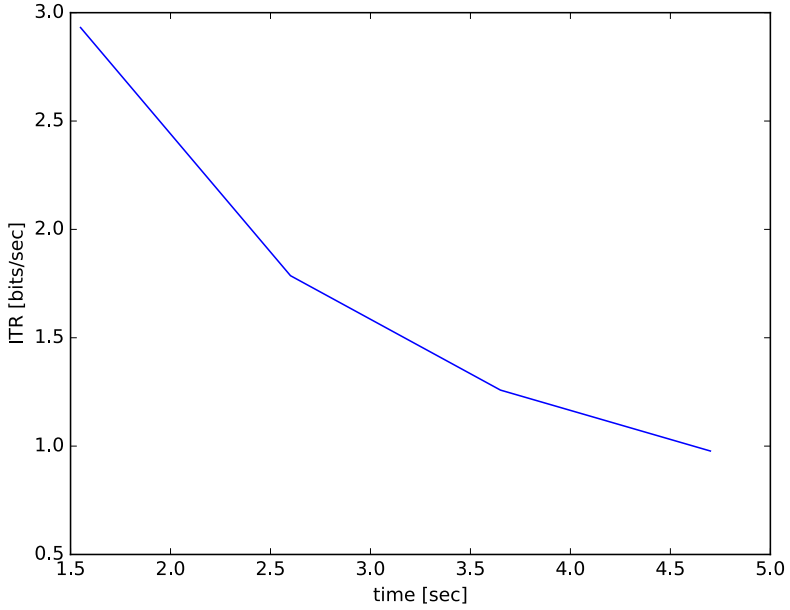
c-VEP

mixed coded SSVEP vs c-VEP : ITR

- To compare [2], The time contains the gaze shifting time (0.5 sec)
- mixed coded SSVEP : 1.92 [bit/sec] (at 1.05 sec + 0.5 sec, M5)
- c-VEP : **2.93 [bit/sec]** (at 1.05 + 0.5 sec sec)



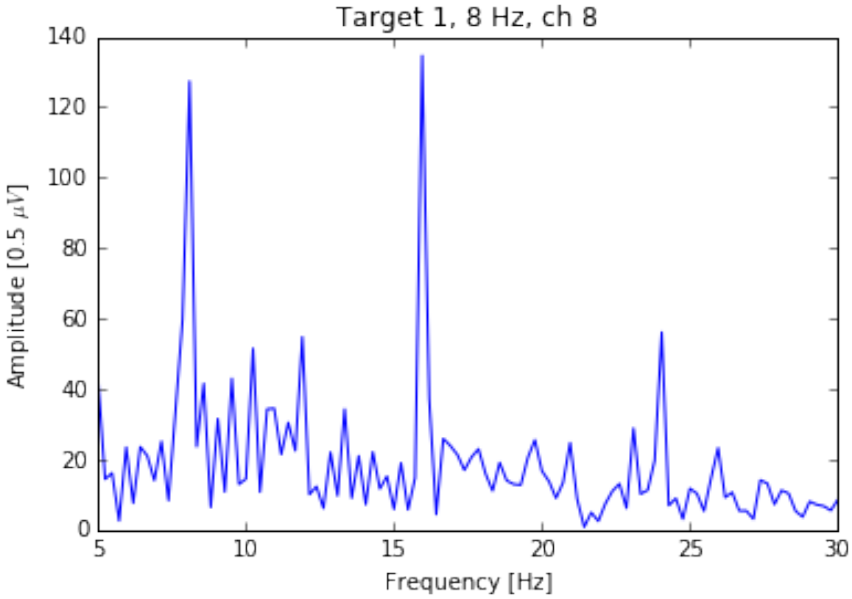
mixed coded SSVEP

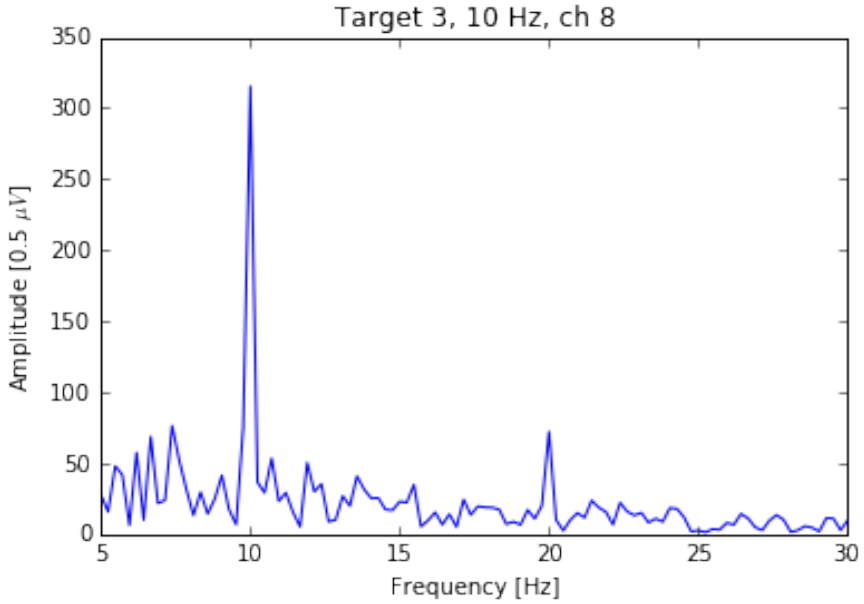


c-VEP

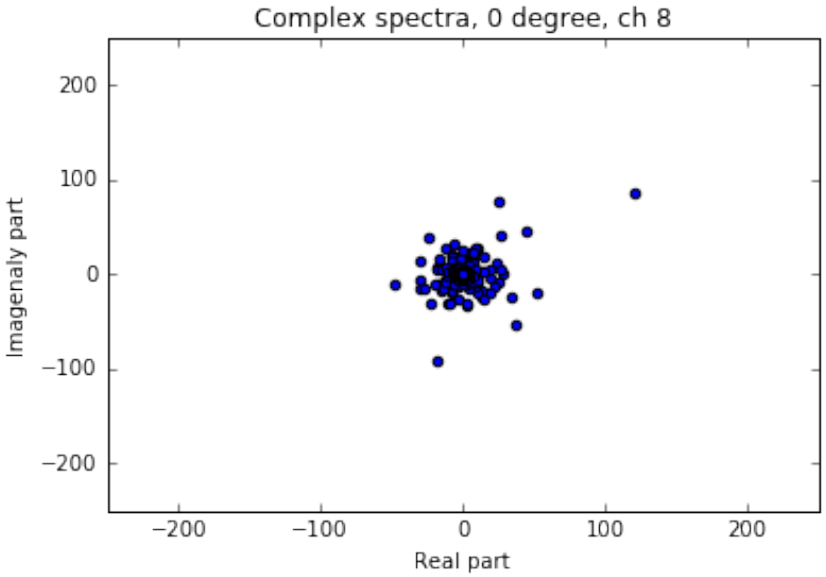
Spectrum Analysis

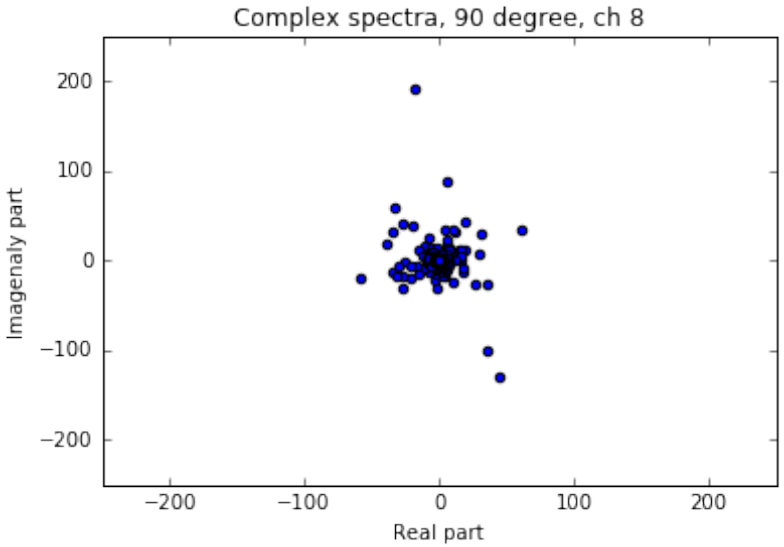
- The target frequency components was observed clearly

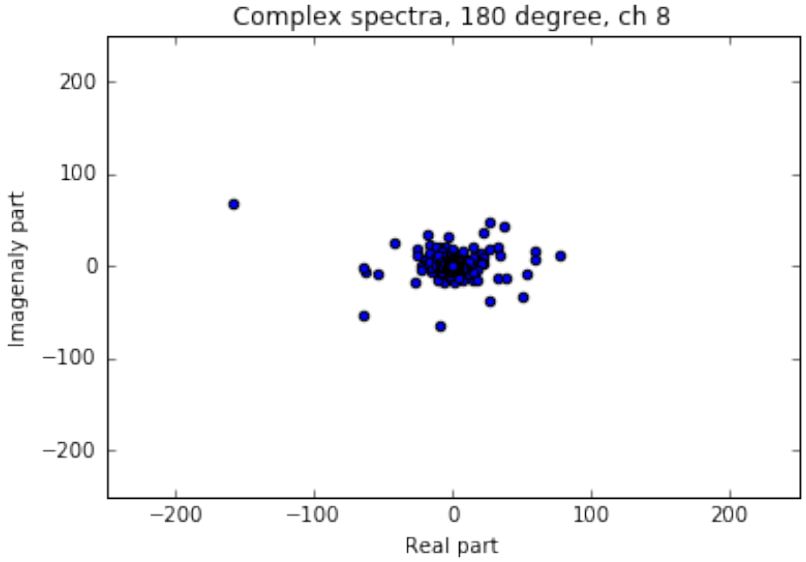


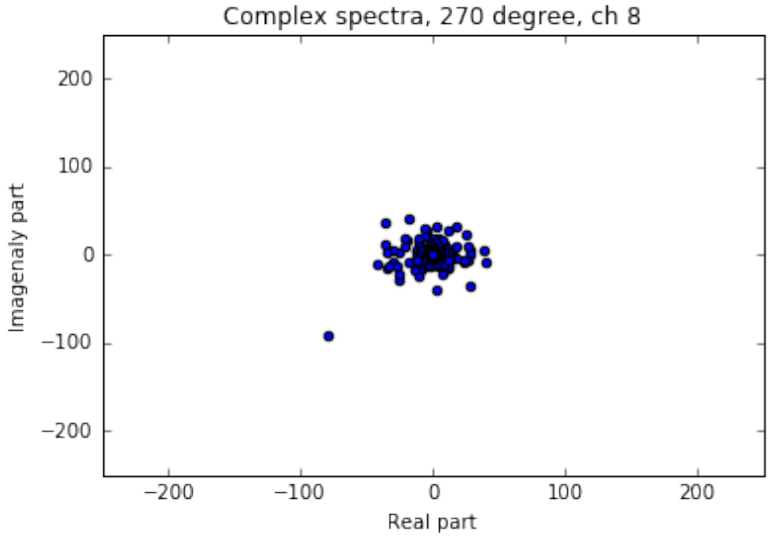


Mixed coded SSVEP : Complex spectra









Optimized combined decision : Logistic Regression

- Optimized weight w_{i} is given by logistic regression

$$\tilde{\rho}_k = \sum_{i=0}^{4} w_{\mathrm{i}} \cdot \rho_i^{(k)}$$

  - $\rho_0 = 1$: bias
  - $k : k = 1, \ldots, 32$, target index
  - label t_n:
    - when k is the gazed target $t_n = 1$
    - when k is not the gazed target $t_n = 0$

- The probability is given by

$$p_k = \frac{1}{1+\exp(-\tilde{\rho}_k)}$$

- Predicted label is,

$$\underset{k}{\operatorname{argmax}}\ p_k$$

Optimized combined decision : Logistic Regression (2)

- Experiment
  - training and test were divided into two (hold out, not cross validation)

- M5 (conventional)
  - 89.58 %
- Logistic Regression (Proposed)
  - 85.50 %

- Proposed method is lower than M5,
  We need to do cross validation

Discussion

- In the paper [2], the average of offline classification accuracy was 88.8 % (at 1 sec), ITR was 161 [bits/min] (2.68 [bits/sec])
- My result of SSVEP is lower than the paper [2],
  This is caused by
  - Electrodes condition (8~16 ch were not good)
  - The number of trainings is few (paper [2] : 7 runs, my experiment : 6 runs)
  - Individual differences
- In the paper [2], online experiment was also compared,
  I should do online experiment
- In c-VEP experiment, I used conventional CCA spatial filter,
  I can use my old research filters (CCF, Neural decoding) to improve the performance

Conclusion and future works

Conclusion

- I did experiments of Mixed frequency and phase coded SSVEP and c-VEP
- In the experiment, c-VEP exhibits higher accuracy and ITR than mixed coded SSVEP

Future works

- More subjects
- Online experiment