Impact of Stimulus Configuration on Steady State Visual Evoked Potentials (SSVEP) Response

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***Abstract*— We investigate the impact of configuration of multi-stimuli presented in computer monitor to steady-state visual evoked potential response. The configuration of stimuli is defined by three parameters-the size of stimuli, the separation distance between the stimuli and the layout. Two 4 by 4 checkerboards in twelve configurations were presented to the subjects. 9 subjects participated in this study. Subjects' electroencephalography (EEG) data was off-line analyzed by using Fast Fourier Transform (FFT). The mean classification rates of configuration with bigger size and larger separation distance is higher than those configurations with smaller size and shorter separation distance. These results suggest that the stimulus size is the most important parameter of three, followed by the separation distance and layout.**

Keywords- Steady-State Visual Evoked Potential (SSVEP); Brain Computer Interface (BCI); Electroencephalography (EEG).

I. INTRODUCTION

Brain computer interfaces (BCIs) give their users communication and control channels that do not depend on the brain's normal output channels of peripheral nerves and muscles [1]. BCIs allow people with severe motor disabilities to communicate with the environment or control device through an alternative channel, which does not depend on normal motor output of the nervous system [2][3].

BCI requires an input brain signal from the user in order to interpret his or her intent and translate it into a command. BCIs can use invasive or non-invasive methods to access the brain signal. Non-invasive electroencephalography (EEG) based methods are most commonly used due to their properties: ease of use, flexibility, high time resolution, low cost and low risk [4][5]. Several EEG-based BCI paradigms have been successful in conveying EEG signals to control devices [6].

Many brain signals can be recorded with EEG and used as the input of BCIs. One of these is Steady-state-visual-evoked-potential (SSVEP), which some recent studies have shown its advantages of higher accuracy rate, speed, scalability and no/less training required compared to other BCI paradigms [3][7][8].

A practical SSVEP based BCI should enable more than one command, which in turn necessitates the presentation of more than one visual stimulus concurrently. In this study, we focused on the use of the computer monitor as the visual stimulator, which provides greater flexibility and user friendly features in graphic interface than LED.

Current SSVEP BCI studies focus on the comparison of different stimulators [9][10] and signal classification methods [8][11][12][13][14]. The impact of the unattended target to the response of attended target is rarely discussed.

The aim of this study is to investigate the impact of the properties of multi-stimuli in terms of their size, separation distance and their layout on SSVEP response. The results of this study will help the practical SSVEP based BCI design.

The rest of the paper is organized as follows: Section II presents the setup and protocol of the experiment and a description of the data acquisition method. The results are discussed in Section III. The conclusion is presented in Section IV.

II. METHODS

This section explains the setup and protocol of the experiment.

A. Stimulus configurations and parameters

The visual stimuli used in this study were generated by Matlab® and Psychophysics Toolbox Version 3 (PTB-3) [17]. The functions of PTB can create accurately controlled visual stimuli for the experiment. To evaluate the impact of stimuli configurations experiment, two black and white 4x4 checkerboards were presented to the subject on a CRT or LCD computer monitor. Twelve configurations were tested in the experiment.

A configuration is defined by three parameters,

(1) Size of stimulus,
(2) Separation distance between two stimuli and
(3) Layout of the stimuli.

The details of 12 configurations (C1 to C12) and the parameters are listed in Table I.

In this experiment, three criteria were used to select the stimulation frequencies.

(1) The selected frequencies can elicit strong SSVEP,
(2) The selected frequencies cannot be harmonics to each other or have common harmonics under 50Hz and
(3) The frequency pair should have stable frequency output in the stimulation.

We pair all sub-frequencies of the monitor refresh rate to simulate the experiment and get the frequency output.

TABLE I. PARAMETERS OF 12 CONFIGURATIONS USED IN THE EXPERIMENT

Configuration		**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**C8**	**C9**	**C10**	**C11**	**C12**
SIZE	**Big**	●	●			●	●			●	●		
	Small			●	●			●	●			●	●
SEPARATION DISTANCE	**Close**	●		●		●		●		●		●	
	Far		●		●		●		●		●		●
LAYOUT	**Horizontal**	●	●	●	●								
	Vertical					●	●	●	●				
	Diagonal									●	●	●	●

Following these criteria, the simulation results and 75Hz of the refresh rate of the monitor (CRT and LCD), 15Hz and 12.5Hz were used in the experiment.

B. Data Acquisition

A 128 channels EEG cap was placed at each subject's scalp. The middle line of the cap is lined up with nasion and inion. To eliminate the dead skin, EEG abrasive skin prepping gel (Nuprep Gel) was applied to the electrode sites first. To reduce the impedance between scalp and electrode, EEG conductive gel (Electro-Gel) was applied to the same sites. The impedance was kept under 5kΩ. The EEG acquisition hardware and software were SynAmps2 (amplifier) and NeuroScan 4.5 (recording software).

The most significant SSVEP can be recorded at the channels over the visual cortex. 11 channels over visual cortex were selected as signal channels while Cz was chosen as the ground and Fz was chosen as the reference channel. The channel selection is shown in Figure 1. The electrode is AgCl type. The EEG sampling frequency was 2,000 Hz.

C. Protocol

Two 4x4 checkerboards were presented to each subject on a CRT or a LCD screen. Both CRT and LCD monitors can elicit SSVEP responses [9]. There was no significant difference in SSVEP response between these two stimulators. CRT is widely used in BCI studies. However, due to the popularity of LCD, an LCD monitor was also used in this study.

Each configuration had 30-45 trials. Each trial had three phases, fixation phase, stimulation phase and resting phase. During the fixation phase, there is a white cross appearing in the centre of the monitor. During the stimulation phase, two 4x4 checkerboards flickering in different frequencies were presented to the subject. In the resting phase, the screen is blank. The information of last stimulation phase (e.g., the time of the stimulation, mean frequency output of the stimuli, etc.) is displayed on the left upper corner. Three phases are illustrated in Figure 2.

One of the challenges to use monitor as visual stimulator is that the frequencies of the stimuli are restricted to the monitor refresh rate. The stimulating frequencies have to be the sub-frequencies of the monitor refresh rate. This limits the selections of the frequencies.

To avoid visual adaptation, fixation phase takes 2 or 3 seconds randomly. Resting phase takes 7 or 8 seconds randomly. The stimulation phase takes 7 seconds. The sequence of the configuration shown to subject was in fixed order (C1 to C12) for the first 3 subjects but become random in the rest configuration evaluation experiment.

Subjects were asked to attend the left stimulus in horizontal layout, upper stimulus in vertical layout and left upper stimulus in diagonal layout. Each configuration took up to 9 minutes (for 30 trials). There is a break between each configuration.

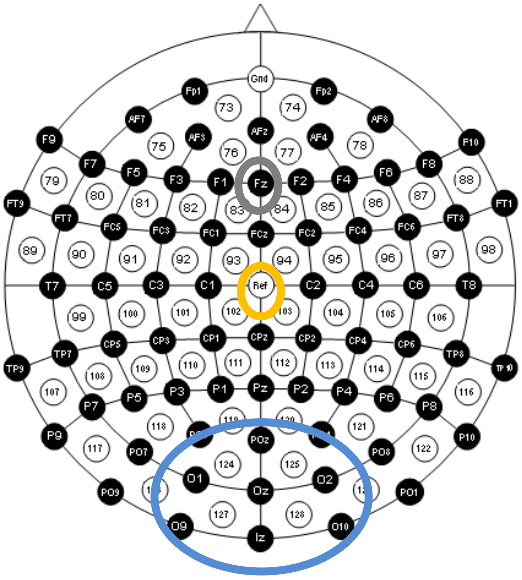
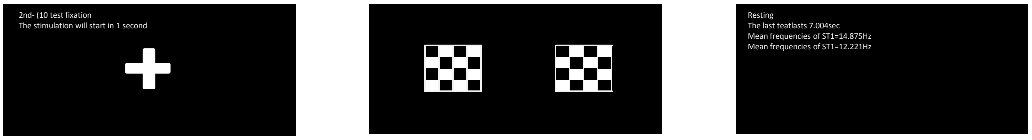


Figure 1. Channel selections. 11 channels inside blue circle were selected as signal channels. Cz (yellow circle) was selected as ground and Fz (grey circle) was selected as reference circle. Channel location is from [18].

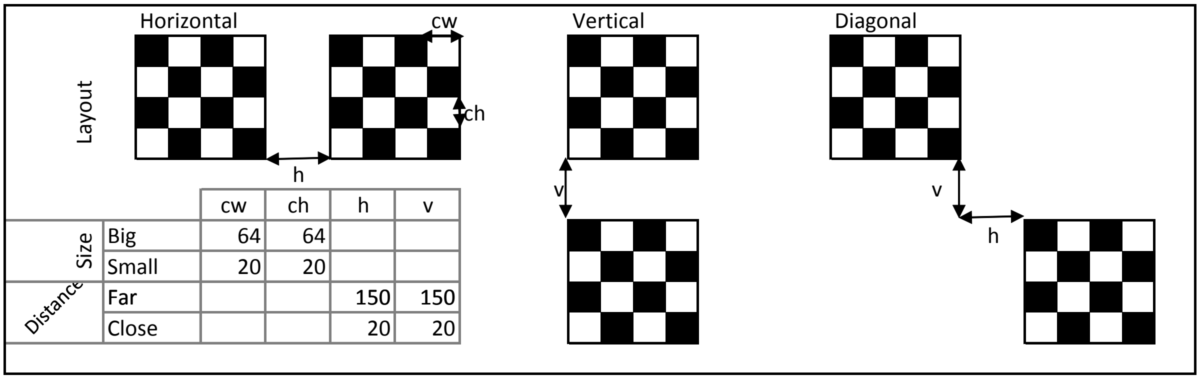


2nd- (10 test fixation
The stimulation will start in 1 second

Resting
The last teatlasts 7.004sec
Mean frequencies of ST1=14.875Hz
Mean frequencies of ST1=12.221Hz

(a) Fixation phase (b) Stimulation phase (c) Resting phase

Figure 2. Three phases in a stimulation trial. (a): fixation phase: a white cross appeared in the centre of the screen (2 or 3 seconds). (b): stimulation phase: two 4x4 checkerboards were presented (7 seconds). (c): Resting phase: blank screen showed information on left upper corner of the screen (7 or 8 seconds).



		cw	ch	h	v
Size	Big	64	64		
	Small	20	20		
Distance	Far			150	150
	Close			20	20

Figure 3. Illustration of the layout and the values of the parameters of configuration

SSVEP based BCI interprets users' intents by analyzing SSVEP response. In order to achieve high accuracy, time length is an important factor. A SSVEP study [15] showed that it requires 2.8 seconds to achieve an average 95% accuracy. Some of the signal classification methods, e.g., FFT requires a longer time window to prevent turbulence caused by spontaneous EEG [16]. The stimulation phase of this study took 7 seconds as we also investigated the impact of time length.

The values of configuration of stimuli are illustrated in Figure 3. The unit of the parameters (e.g., cell width (cw), cell height (ch), horizontal distance (h) and vertical distance (v)) is pixel.

The resolutions of CRT and LCD used in the experiment are 1600x1200 and 1440x900 respectively. Figure 3 shows the setup of CRT. The setup of LCD was slightly different, but the physical visual of size and layout on the screen were similar.

III. DATA ANALYSIS AND RESULT

FFT was applied to the time domain EEG signal. FFT was performed on a single trial/epoch of EEG with different epoch time varying from 1 second to 5 seconds. After FFT was performed, the power of the frequency spectrum at all SSVEP response frequencies will be extracted. The harmonics of SSVEP response frequency, which range from 5Hz to 50Hz were also considered.

Four types of signal combinations used in the analysis: (1) Fundamental: Using the fundamental frequency response only. (2) Fundamental + Sub: Using a combination of the fundamental frequency and the sub-harmonics, which is no lower than 5 Hz. (3) Fundamental + High: Using a combination of the fundamental frequency and the higher harmonics, which is no higher than 50Hz. (4) Fundamental + all: Using a combination of the fundamental frequency and all harmonics between 5 to 50 Hz.

Figure 4 is the average classification rates of all subjects in different configurations. Figure 4 is based on 3 seconds epoch time. Figure 4 shows that, in general, the configurations of big size of stimuli have the higher classification rates than those configurations of smaller size stimuli. The configurations of large separation distance also have higher classification rates than close separation distance if the other two parameters are the same, except C3 and C4. Horizontal layout has higher average classification rates than vertical and diagonal layouts. The results of 4 and 5 second epoch are similar.

A one-way ANOVA analysis was performed to evaluate the effect of configurations to classification rates based on an epoch time of 3 seconds. The classification rates were further divided into four groups. The first three groups are the classification rates of C6, C2 and C1, the configurations, which resulted in the top three highest classification rates, the fourth group is the average classification rates of the remaining 9 configurations, CR. (C2, CR), (C6, CR) and (C1, CR) are compared. The values of $F(1, 6)$ are 27.78, 23.98 and 22.38 respectively with p values 0.0019, 0.0027 and 0.0032. The differences of classification rates between C2, C6, C1 and the rest configurations are significant.

Figure 5 illustrates the classification rates of one subject in different configurations using different signal combinations. Figure 5 is the result of a 4-second epoch.

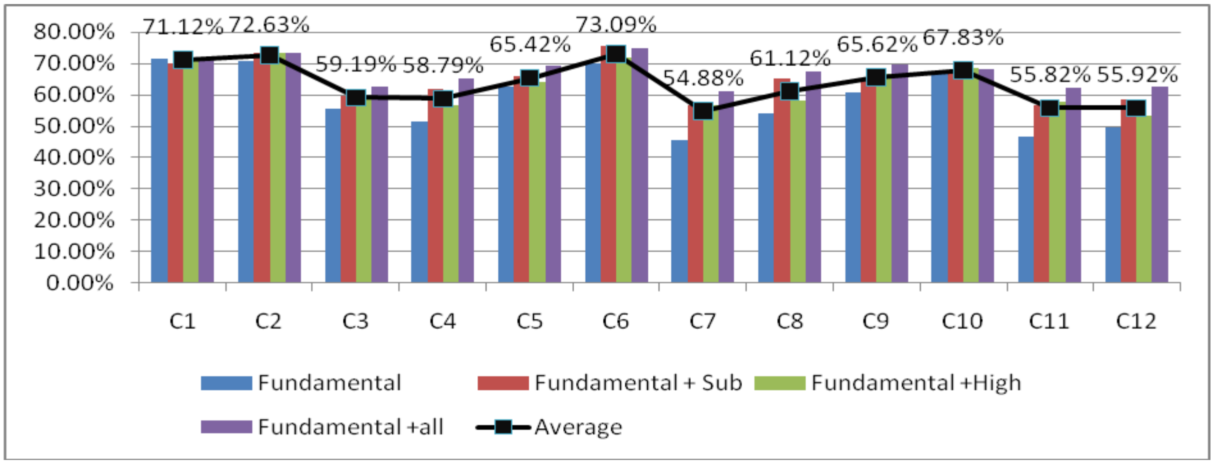


Figure 4. Average classification rates of all subjects of different signal combinations in different configurations. This figure is based on 3 seconds epoch.

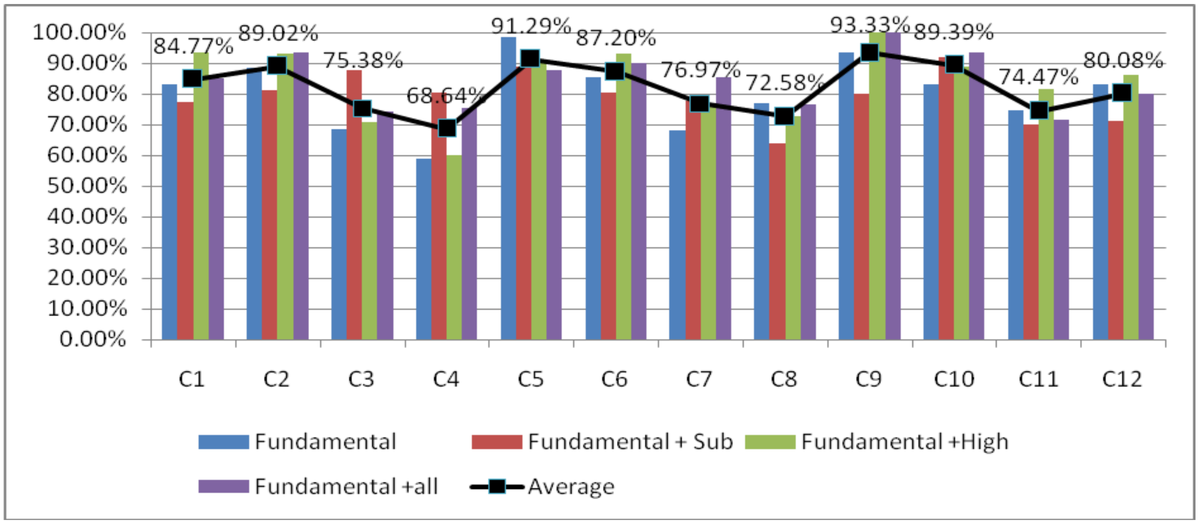


Figure 5. Classification rates of one subject of different signal combinations in different configurations.

Generally speaking, the configurations of a big size stimulus can yield a higher classification rate than the small size regardless of the layouts and separation distances. Large separation distance has higher rates if the size of stimulus is the same and layout is the same. The results from other subjects show a similar trend.

In order to understand the configuration better, four possible outcomes are further defined as following.

(1) True positive. This is when the response of the selection is the highest of the responses, which exceed the threshold. The number of true positives is referred to as a_{11}.

(2) Aliasing. This is when both responses at the stimulating frequencies exceed the threshold but the response at un-attended target is stronger than the one selected. The Aliasing is referred to as a_{12}.

(3) False positive. Only the response at the un-attended exceeds the threshold. The number of false positive is referred to as a_{21}.

(4) No response. None of the responses exceed the threshold. No response is referred to as a_{22}.

These four parameters provide another perspective view on the impact of the configurations on elicited SSVEP. The same elements of the matrix of each subject using the same signal combinations were added. a_{11} is used to examine the number of proper SSVEP responses; we use a_{12} to examine the number of aliasing responses caused by un-attended frequency; use a_{21} to examine the number of false positive and use a_{22} to examine the number of no SSVEP responses.

Table II shows the grand total of true positive, aliasing, false positive and no response of all subjects of all different epoch time (1 to 5 seconds).

It is clearly seen from Table II that C2 and C6 have the overall best performance in all configurations with more true positive and less aliasing, false positive and no response.

Table III is one subject’s analysis result in all configurations with different signal combinations. This table is based on an epoch time of 4 seconds.

TABLE II. GRAND TOTAL OF TRUE POSITIVE, ALIASING, FALSE POSITIVE AND NO RESPONSE OF ALL SUBJECTS OF ALL DIFFERENT EPOCH TIME (1 TO 5 SECONDS).

overall	**Fundamental**				**Fundamental + sub**				**Fundamental + high**				**Fundamental + all**			
	a_{11}	a_{12}	a_{21}	a_{22}	a_{11}	a_{12}	a_{21}	a_{22}	a_{11}	a_{12}	a_{21}	a_{22}	a_{11}	a_{12}	a_{21}	a_{22}
C1	7,520	3,748	602	505	7,741	4,289	261	84	7,976	3,557	393	449	8,071	4,011	228	65
C2	8,048	3,777	459	421	8,255	4,095	199	156	8,386	3,715	368	236	8,428	4,091	139	47
C3	6,692	4,961	820	727	7,293	5,533	214	160	7,057	4,768	819	556	7,369	5,445	211	175
C4	6,009	4,762	1,272	662	7,447	4,816	239	203	6,540	4,588	949	628	7,592	4,751	236	126
C5	7,116	4,518	616	455	7,663	4,645	248	149	7,311	4,395	486	513	7,863	4,490	206	146
C6	7,597	4,038	573	497	8,134	4,238	197	136	8,340	3,519	429	417	8,482	3,930	216	77
C7	5,236	5,071	1,451	947	6,390	5,603	481	231	5,860	4,752	1,140	953	6,751	5,313	390	251
C8	5,704	4,557	1,347	1,097	7,087	4,767	524	327	6,117	4,424	1,089	1,075	7,292	4,530	511	372
C9	6,886	4,153	807	859	7,214	4,720	392	379	7,170	3,920	532	1,083	7,666	4,252	399	388
C10	7,445	3,602	614	1,044	7,551	4,243	464	447	7,464	3,643	513	1,085	7,746	3,979	359	621
C11	5,319	4,676	1,314	1,396	6,499	4,935	622	649	5,843	4,555	902	1,405	6,845	4,709	401	750
C12	5,232	4,396	1,437	1,640	6,106	4,954	797	848	5,689	4,337	1,075	1,604	6,534	4,679	643	849

TABLE III. NO OF TRUE POSITIVE, ALIASING, FALSE POSITIVE AND NO RESPONSE OF ONE SUBJECT IN DIFFERENT CONFIGURATION

	Fundamental				**Fundamental + sub**				**Fundamental + high**				**Fundamental + all**			
	a_{11}	a_{12}	a_{21}	a_{22}	a_{11}	a_{12}	a_{21}	a_{22}	a_{11}	a_{12}	a_{21}	a_{22}	a_{11}	a_{12}	a_{21}	a_{22}
C1	233	64	33	0	242	88	0	0	315	15	0	0	286	44	0	0
C2	275	55	0	0	286	44	0	0	297	33	0	0	286	44	0	0
C3	214	77	11	28	231	86	13	0	281	38	0	11	253	77	0	0
C4	176	117	26	11	220	99	11	0	252	78	0	0	242	88	0	0
C5	231	66	33	0	168	129	33	0	242	78	10	0	206	124	0	0
C6	220	88	22	0	187	143	0	0	280	50	0	0	220	110	0	0
C7	111	163	34	22	121	165	44	0	185	145	0	0	176	154	0	0
C8	222	97	11	0	207	103	20	0	275	55	0	0	275	55	0	0
C9	132	112	53	33	111	179	29	11	209	90	9	22	184	124	22	0
C10	148	87	45	50	133	142	44	11	231	77	22	0	206	124	0	0
C11	90	44	99	97	143	102	74	11	255	64	11	0	224	84	22	0
C12	154	54	89	33	154	109	67	0	231	77	22	0	202	115	13	0

This table indicates that the configurations of big size stimulus and large separation distance can produce more true positive while reduces the number of aliasing, false positive and no response, e.g., C2. While the configurations of small size stimulus, has less true positive and produce more aliasing and/or false positive and/or no response, e.g., C7, C11.

IV. CONCLUSION

From the analyzed in last session, it is clear that the size of stimulus plays the most important role in the configuration parameters, followed by separation distance and followed by the layout. We conclude that the configurations with big stimulus size, like C1, C2 and C6 can result in better SSVEP response with less aliasing.

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