Experimental validation on dual-frequency outperforms single-frequency SSVEP with large numbers of targets within a given frequency range

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***Abstract*— Multi-frequency steady-state visual evoked potential (SSVEP) aims to increase the number of targets in SSVEP-based brain-computer interfaces. However, the effectiveness of multi-frequency SSVEP when there is a large number of targets compared to traditional single-frequency SSVEP has not been demonstrated to date. It is also unclear the degree to which multi-frequency SSVEP outperforms single-frequency SSVEP as the number of targets increases. This study directly compares single-frequency and dual-frequency SSVEPs for different numbers of targets within a fixed (5 Hz) frequency range. Our results demonstrate that dual-frequency SSVEP maintains its performance at a high level of accuracy in the range while single-frequency SSVEP performance falls as the number of targets becomes very high within the given frequency range. In this particular study, dual-frequency SSVEP has a clear advantage when there are more than 120 targets in a 5 Hz frequency range.**

I. Introduction

The steady-state visual evoked potential (SSVEP) is a type of brain activity that is widely used in non-invasive brain-computer interfaces (BCIs) [1]. SSVEP is a reactive response of the brain in reaction to periodically flickering stimulation [2], where the measured SSVEP contains the same frequency as the stimulus plus its harmonics [3], [4].

The traditional setup in SSVEP-based BCIs is to have multiple stimuli laid out in the environment, each representing one command or a letter on a keyboard, and each stimulus or target is labelled with a unique frequency of periodic stimulation. The interface determines the user's intention by checking the frequencies in the measured EEG against the list of designed stimulation frequencies. This is an effective and efficient setup for tasks that have a small number of targets to select from, such as four targets – up, down, left, and right – for vertical 2D navigation on a screen. However, due to the limited responsive range and the existence of harmonics in SSVEP [3], it is challenging to work with complex tasks that include large numbers of targets.

Multi-frequency SSVEP stimulation methods [5]–[9], decoding algorithms [10], [11], and optimisation methods [12], [13] have been developed to increase the number of representable and identifiable targets. Even though it was claimed in the above-mentioned studies that multi-frequency SSVEP could effectively extend the capabilities of SSVEP-based BCIs, it is still not clear if and by how much multi-frequency SSVEP will improve the performance of the interface with large numbers of targets compared to single-frequency SSVEP and, more importantly, if it is possible to tell which one might be more suitable given specific task and system requirements.

In this study, a comparison between single-frequency and dual-frequency SSVEP was conducted to investigate dual-frequency SSVEP performance relative to standard single-frequency SSVEP. Since the purpose of introducing dual-frequency SSVEP is to enable the presentation of a large number of targets, we examine the effectiveness of dual-frequency SSVEP vs. single-frequency SSVEP over different numbers of targets in a fixed frequency range. In single-frequency SSVEP, more targets over a given frequency range results in narrower intervals between frequencies to be identified. This increases the chance of misidentification. Thus, it is expected that there will be a point, in terms of number of targets over a limited frequency range, where identification accuracy will degrade. The use of two frequencies to represent each target allows more combinations to be constructed by pairing fewer unique frequencies in the same frequency range. Therefore, dual-frequency SSVEP is hypothesised to result in better decoding accuracy while the single-frequency approach degrades. This study provides the first experimental validation of the hypothesis that utilising multi-frequency stimulation in SSVEP is effective in maintaining performance accuracy beyond the point where single-frequency SSVEP fails due to the high relative number of targets to the given frequency range.

II. Methods

To constrain the size and duration of the study, we used a 5 Hz frequency range (11-16 Hz, inclusive) to demonstrate the concept; however, this can be generalised to a wider frequency range. The 11-16 Hz range was selected so that it was within the low frequency responsive range of SSVEP [3] and avoided including multiples of a frequency (harmonics) in the same range. Based on this 5 Hz frequency range, the required number of frequencies (N_F) and the frequency intervals (ΔF) for different numbers of targets (N_T) were calculated, assuming all frequencies were evenly spaced within the range; these are listed in Table I. Essentially, the frequency density, which is the number of unique frequencies used as stimulation to label each target with a single-frequency

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TABLE I: Calculated numbers of frequencies and frequency intervals in single-frequency and dual-frequency setups over a frequency range of 5 Hz.

N_T	$N_{F,\text{single}}$	$N_{F,\text{dual}}$	ΔF_{single} (Hz)	ΔF_{dual} (Hz)
15	15	6	0.3571	1.000
50	50	11	0.1020	0.5000
100	100	15	0.0505	0.3571
150	150	18	0.0336	0.2941
200	200	21	0.0251	0.2500
500	500	33	0.0100	0.1563
1000	1000	46	0.0050	0.1111

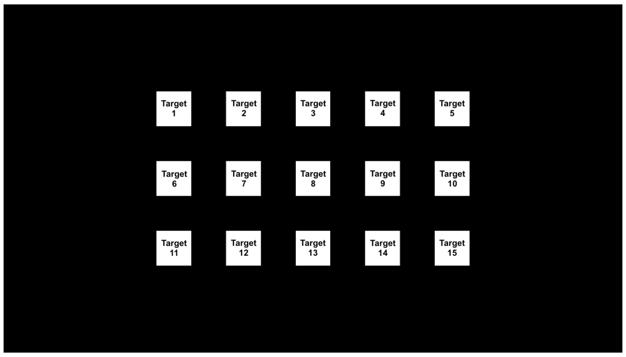


Fig. 1: Stimuli layout on the screen.

SSVEP or dual-frequency SSVEP over a fixed frequency range, was investigated. The numbers of frequencies in the dual-frequency setup ($N_{F,\text{dual}}$) were then calculated as the smallest integer satisfying

$$C_2^{N_{F,\text{dual}}} \geq N_T, \tag{1}$$

where C_k^n is the n choose k combination operator with n being the number of elements or objects and k is the number of samples.

With considerations of experiment duration and balanced tests, we tested all cases with a 15-target layout; in other words, only 15 frequencies or frequency pairs were tested in each case, arranged to realise the corresponding frequency density over the 5 Hz range. The lowest 15 frequencies in single-frequency cases and 6 frequencies ($C_2^6 = 15$) in dual-frequency cases were selected for testing. The full lists of frequencies tested are shown in Table II. Here, $a\!:\!b\!:\!c$ means an array from a to c with increments of b; e.g., $11\!:\!1\!:\!16 = [11, 12, 13, 14, 15, 16]$.

A. Experimental Setup

The interface used in this experiment was programmed in Unity (Unity Technologies, USA) with event information, such as trial onset and trial outcome, exchanged with Simulink (The MathWorks, Inc., USA) in real time using the user datagram protocol (UDP). Participants sat 70 cm away from an Alienware monitor AW2518HF (24.5 inch, 1920×1080; Dell, USA) that displayed the stimuli. The screen was centred and adjusted to suit each participant's height. Experiments were done in a dim, quiet room.

The stimuli were in white colour of size 108 × 108 pixels and 108 pixels apart in horizontal and vertical directions. The 15 targets were laid out in a 3× 5 grid as shown in Fig. 1.

7	3	6	4	10	1	8	5	9	2
9	1	5	8	2	4	10	7	3	6
3	8	1	2	6	5	9	4	7	10
10	4	7	9	5	2	1	3	6	8
4	5	8	10	9	6	7	2	1	3
6	7	2	1	3	9	5	10	8	4
8	9	3	5	7	10	4	6	2	1
2	10	4	6	1	7	3	8	5	9
1	2	10	7	8	3	6	9	4	5
5	6	9	3	4	8	2	1	10	7

Fig. 2: Example of a 10-by-10 Sudoku in brickwall style.

Single-frequency stimulation was delivered using 50% duty cycle square waves on the screen at full brightness. Dual-frequency stimulation was delivered using frequency superposition ADD logic [9] with two 50% duty cycle square waves at half brightness (the stimulation was at full brightness when both were HIGH).

EEG data was recorded with g.USBamp EEG system and g.SAHARA dry electrodes (g.tec medical engineering, Austria) at 512 Hz. A 50 Hz notch filter and a $0.5 - 100$ Hz band pass filter were applied to all channels in the g.USBamp recording settings. Data was recorded from 16 channels (P3, Pz, P4, PO3, POz, PO4, O1, Oz, O2, Fz, FCz, FC1, FC2, Cz, C1, and C2); however, only the first 9 channels near visual cortex were used in data processing. Reference and ground electrodes were placed on the left and right mastoids, respectively.

Five participants (four males, one female) aged 26-30 years (27.60 ± 1.52) participated in this experiment. The experiment was approved by the University of Melbourne Human Research Ethics Committee (Ethics ID 1851283). Written consent was collected from each participant prior conducting the experiment.

B. Experimental Protocols

Ten different setups were tested (with setup numbers 1 to 10, Table II). In order to balance setups across users, 10-by-10 Sudokus in brickwall style, as shown in Figure 2, were used to order experiments across participants. Each participant was tested for three sessions with each session containing 10 tests (10 setups, 1 test per setup), so that each setup was repeated three times. Two rows were used by each participant from the Sudoku, with each 2-by-5 block being a session, the two rows separated the block into two 5-test parts that corresponded to the two parts in each session. In total, 1.5 Sudokus were used to make three sessions.

Each test had 15 trials (15 targets, 1 trial per target). The trial structure is depicted in Fig. 3. Each trial started with a 1 s cue (green outline of intended target), followed by 5 s stimulation (with a fixation point at the centre of the intended target, all targets were flashing during this stimulation period), then 1 s feedback was provided to keep participants engaged (solid green or red square to indicate successful or erroneous identification, respectively) [14], and finally 1 s rest. A score was shown to the participant after each completed test indicating the number of correct trials for the test with 0 indicating none of the 15 trials was identified correctly and 15 indicating all trials were correctly identified.

TABLE II: Frequency intervals and frequencies selected for the experiment in both single-frequency and dual-frequency cases and the matching number of targets in a 5 Hz frequency range.

Equivalent N_T over 5 Hz Range	Single			Dual		
	Interval (Hz)	Frequencies (Hz)	Setup Number	Interval (Hz)	Frequencies (Hz)	Setup Number
15	0.35	11:0.35:15.9	1	1	11:1:16	6
50	0.1	11:0.1:12.4	2	0.5	11:0.5:13.5	7
100	0.05	11:0.05:11.7	3	0.35	11:0.35:12.75	8
200	0.02	11:0.02:11.28	4	0.25	11:0.25:12.25	9
500	0.01	11:0.01:11.14	5	0.15	11:0.15:11.75	10

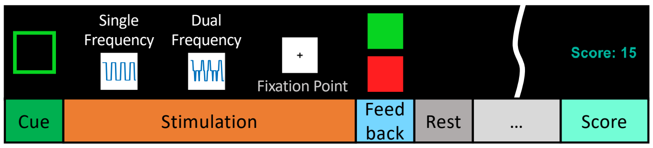


Fig. 3: Trial structure.

A one-minute break was provided after each test and 5-10 min breaks were placed between the sessions. The length of breaks were adjusted to the participant's need.

In each test, the participant was asked to go through each of the 15 targets one-by-one following the cue. To simplify the participant's task in each test, the trial sequence was always from left-to-right, top-to-bottom, going through the targets in target index ascending order (Fig. 1). However, the stimulation frequencies or frequency pairs were randomly shuffled among the 15 targets.

To ensure participants were familiarised with the experiment tasks, a training session was included at the beginning of the experiment using single frequencies 8:0.5:15 Hz and dual-frequency pairs with 8:1:13 Hz combinations to make the 15 targets. This was run at least two times until the participant felt comfortable with the task.

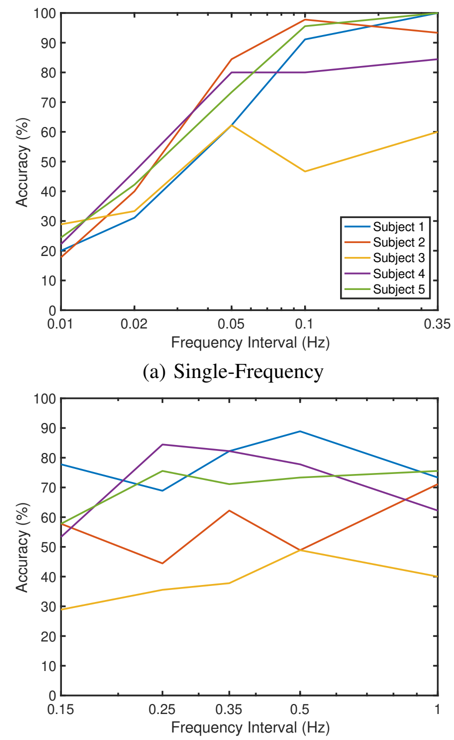
C. Data processing

To calculate performance and generate feedback to the participants, the 5 s recording from each trial was decoded using canonical correlation analysis (CCA) [15] with number of harmonics set to 3 in single-frequency setups and multi-frequency canonical correlation analysis (MFCCA) [10] with order set to 1 in dual-frequency setups. In this work, we compare the accuracy of the interface under different stimulation setups. The accuracy is calculated as the correctly identified trials (the score) divided by the total number of trials (15).

III. Results

Figure 4 shows the average accuracy from each participant in both single-frequency and dual-frequency SSVEP. Note that the horizontal axes here are in log scale. These two plots show that accuracy fell significantly with single-frequency at frequency intervals less than 0.05 Hz, whereas dual-frequency SSVEP was almost constant for all participants.

Figure 5 shows the means and 95% confidence intervals of the accuracy of single-frequency and dual-frequency SSVEP at different frequency intervals. The means and 95% confidence intervals were obtained by bootstrapping [16] (10000 times) with all participants' results from all sessions (5 participants × 3 sessions = 15 samples) as some of our



(a) Single-Frequency

(b) Dual-Frequency

Fig. 4: Average accuracy of (a) single-frequency and (b) dual-frequency SSVEP against the frequency intervals for each participant.

results were not normally or evenly distributed. It can be seen that single-frequency had higher accuracy when the same frequency intervals were used in both single- and dual-frequency stimulation; however, accuracy in single-frequency dropped rapidly when the frequency interval became smaller than 0.1 Hz. In dual-frequency, the accuracy held almost constant, with a slower decrease when frequency interval was smaller than 0.35 Hz.

By mapping the frequency intervals to the number of targets in Table II, Figure 6 was created from Figure 5 as an illustration of how accuracy from single-frequency and dual-frequency SSVEP would change with number of targets within the 5 Hz frequency range if full tests on all possible targets could be done. E.g., performance at 0.1 Hz interval in single-frequency from Figure 5 is matched to Figure 6 at 50 targets. From Figure 6, we can see that, when the number of targets exceeds 120 (approximately), dual-frequency stimulation would outperform single-frequency stimulation in terms of mean accuracy. It also shows that dual-frequency stimulation would have a slower decrease in

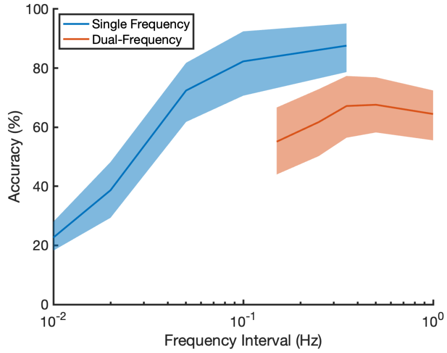


Fig. 5: Accuracy of single-frequency vs. dual-frequency SSVEP against the frequency intervals. Solid lines show the mean accuracy and shaded areas show 95% confidence interval.

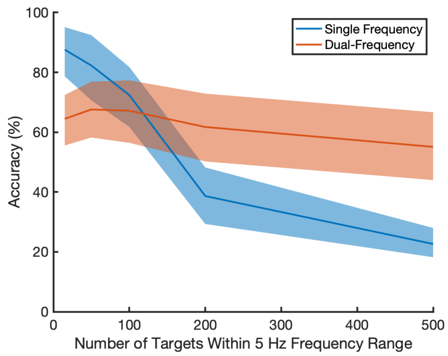


Fig. 6: Accuracy of single-frequency vs. dual-frequency SSVEP against the number of targets within a 5 Hz frequency range.

accuracy as the number of targets increases.

IV. Discussion

Our results showed that single-frequency SSVEP had higher accuracy than dual-frequency when the same frequency interval was used. The difference in performance is likely due to the complex frequency patterns (linear interactions) in dual-frequency SSVEP [9] that were shown to have negative impact on accuracy if not dealt with carefully [13]. This suggests that, under the same frequency interval condition, single-frequency is superior to dual-frequency when considering accuracy and ease of setting up. However, the main advantage of dual-frequency is that it allows larger frequency intervals compared to single-frequency when the number of targets is large, as it reduces the number of unique frequencies needed to represent the same number of targets. From our results, we can see that the accuracy decreased as the frequency interval became narrower, with a rapid drop in accuracy when single-frequency had a frequency interval of less than 0.1 Hz. A performance drop at 0.05 Hz interval compared to 0.1 Hz was also observed by [17]. This demonstrates the advantage of dual-frequency SSVEP when a large number of targets is needed over a restricted frequency range, e.g. over 120 targets in a 5 Hz frequency range. Note that, in both experiments, dry EEG electrodes were used, which may result in a 20% accuracy difference (lower) compared to using wet electrodes [18].

V. Conclusion

In this study, the advantage of multi-frequency SSVEP was demonstrated through experimental results, which showed that the accuracy of a SSVEP-based BCI can be maintained at a higher level with multi-frequency SSVEP beyond the point where single-frequency SSVEP performance degrades due to the high relative number of targets for a given frequency range.

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