High Frequency Steady-State Visual Evoked Potentials: An Empirical Study on Re-test Stability for Brain-Computer Interface Usage

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Abstract: Steady-State Visual Evoked Potentials (SSVEP) constitute an established approach to operate a Brain-Computer Interface (BCI). In contrast to stimulation between 13 and 17 Hz, stimulation above 30 Hz is considered less annoying and diminishes the risk of epileptic seizures. However, high-frequency BCIs usually feature slow processing speed and accuracy rates which reduces user satisfaction. We investigate the re-test stability of resonance frequencies between 30 and 50 Hz in 18 participants over a period of 40 days, including seven consecutive runs. Aim is to determine individual resonance profiles for recurring BCI usage that make time-consuming calibration phases no longer necessary. Preliminary findings of a clinical sample are reported as well. Results indicate that seven of nine frequencies fail to repeatedly induce stable responses. However, stimulation with 32 and 40 Hz induced strong and recurring SSVEP in the vast majorities of trials. Consequently, high-frequency based BCI usage will continue to presuppose individual calibration. Apart from this, since 40 Hz oscillations are suggested to play a key role in various brain functions, it is reasonable to assume pronounced cortical reactions to 32 Hz to also constitute a neuronal oscillator that is functional active during cognitive processing.

1 INTRODUCTION

Intermittent photic stimulation (IPS) of frequencies at a rate of 4 Hz or higher evokes a synchronized cortical response of rhythmic activity linked to the triggering frequency (Herrmann, 2001). Oscillatory EEG activity that arises from repetitive stimulation is referred to as Steady-State Visual Evoked Potentials (SSVEP) and constitutes an important clinical test to detect photoparoxysmal responses. Recorded primarily over early visual processing areas of the brain, it is assumed to occur due to neuronal oscillators that selectively respond to predetermined frequencies, so-called resonance frequencies (Makeig et al., 2002). Amplitudes of SSVEP activity seem to peak at 15 Hz (Pastor et al., 2003) but are also reported to be correlated with the EEG alpha-range (8-12 Hz), indicating strongest responses near a dominant resting frequency (Jin et al., 2000; Ehlers et al., 2012). A previous study (Herrmann, 2001) demonstrates the origin of SSVEP activity up to 100 Hz and reports pronounced cortical reactions to flickering stimuli in the 10, 20, 40 and 80 Hz range compared to adjacent frequencies.

In the recent past, SSVEP activity has been applied successfully to operate a Brain-Computer Interface (BCI) (Stawicki et al., 2016; Chabuda et al., 2018). A BCI is a non-muscular communication system that classifies EEG activity patterns and translates them in real time into commands for various applications. As indicated above, SSVEP-based BCIs require overt attentional shifts between constant flickering sources whereas each stimulation frequency is associated with a certain command. Usually, SSVEP frameworks apply stimulation between 13 and 17 Hz since this range is known to produce prominent and easy to detect SSVEP (Allison et al., 2010; Ehlers et al., 2012; Stawicki et al., 2016). However, visual annoyance and photosensitivity pose a problem, especially in this particular spectrum. As a consequence, recent research focuses IPS above 30 Hz. Higher frequency

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stimulation has proven to reduce the risk of epileptic seizures and is usually considered less annoying during long-term usage (Molina, 2009; Müller et al., 2015; Chabuda et al., 2018). Due to poor signal-to-noise ratios (SNR), however, processing speed of a high frequency SSVEP framework is comparably slow and associated with considerably lower accuracy rates (Molina, 2009; Ehlers et al., 2012).

Similar to SSVEP activity during low frequency stimulation, induced cortical reactions between 30 and 46 Hz seem to occur selectively and feature inter-individual differences (Ehlers et al., 2012; Stawicki et al., 2016; Chabuda et al., 2018). Current SSVEP-based frameworks above 30Hz (e.g. Chabuda et al., 2018) apply time-consuming calibration phases prior to BCI usage to detect prominent resonance frequencies. However, it's not clear whether a once-identified individual frequency set will provide the same resonance performance during repeated usage. To our knowledge, the re-test stability of resonance frequencies above 30 Hz over a longer period has not been investigated yet. Repeated stimulation carried out over several test days should enable to detect temporally stable oscillators that produce distinct and recurring SSVEP and make time-consuming calibration no longer necessary. For this purpose, the current study applies four consecutive sessions with varying time intervals in-between. In controlled settings, nine stimulation frequencies between 30 and 46 Hz are inspected for SNRs and re-test stability over a period of 40 days. Furthermore, initial results with regard to a clinical pilot study are provided to give an impression of cortical reactions to flickering stimuli in potential target users.

2 METHODS

2.1 Design and Procedure

To test the stability of induced driving responses, SSVEP screenings were arranged in four sessions, including two runs of nine randomized trials in two LED-on phases each (figure 1). Intervals between sessions were controlled as follows: 1st session / 2nd session: 1st session + 2 days / 3rd session: 2nd session + 1 week / 4th session: 3rd session + 1 month. Due to the availability of our participants, daytimes could not be controlled and varied between 10:00 am and 16:00 pm. Lab environment exhibited a common level of background noise, lighting conditions were kept constant at 780 lux.

Participants were seated in a comfortable chair, 40 cm in front of an LED array. LEDs had an edge length of 20x14 mm and were marked in ascending order with numbers from 1 to 4; vertical angle of vision was 0.3°. The experimenter indicated a specific number before start and participants were instructed to focus the given LED during a complete trial of 8,75 seconds. Nine frequencies between 30 and 46 Hz (in a step of 2 Hz: 30, 32, 34, 36, 38, 40, 42, 44, 46) were assigned in randomized order at varying positions on the array. Since IPS of just under four seconds is sufficient to selectively induce resonance properties (Molina, 2009), each frequency was tested in two successive LED-on segments of 3.75 seconds with an LED-off segment of 1.25 seconds in between. After a five-minute rest, screening procedure was repeated. The fourth session consisted of only one run. Accordingly, each volunteer participated in seven screenings. Flickering frequencies were controlled by a microcontroller (PIC16F877, Microchip, Chandler, Arizona, USA).

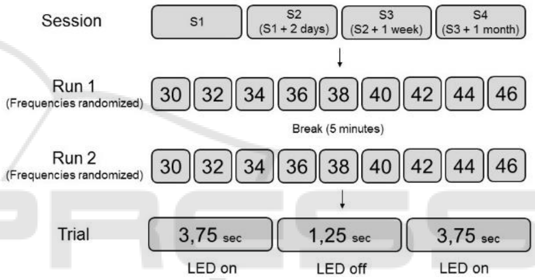

Figure 1: Overall testing procedure.

Additionally, a pilot study on high frequency SSVEP activity in potential BCI target users was carried out in a usual working area. Moreover, except for stimulation frequencies and trial duration, experimental setup and testing equipment differed strongly from the current specifications. Frequencies were randomly assigned to four square shaped LEDs (edge length: 7x7 cm) arranged around a computer monitor. Viewing distance and environmental conditions could not be controlled. Also, due to state of health, patients performed only a single session including two runs. For more details on the SSVEP framework see (Ware et al., 2010).

2.2 Participants

18 volunteers (16 females; mean age: 24 years, SD: 4) were included in the current study. Participants had normal or corrected-to-normal vision and no prior experiences with BCIs. They reported no history of head injury and no neurological or psychiatric disorder. Participants were informed that repetitive stimulation might lead to epileptic seizures and

confirmed that they never suffered from epilepsy or any photosensitive reactions. Information on regular medication was not collected. Participants received course credits, written informed consent was obtained prior to the start.

The clinical sample consisted of 16 potential BCI target users (three females; mean age 40 years, SD: 11) that were tested on basis of a differing SSVEP setup. These volunteers were recruited from the Cedar Foundation (Belfast, Northern Ireland), a non-profit organization that supports people with various disabilities. The sample included patients that suffer from severe handicaps due to brain/spine injuries, stroke or cerebral palsy.

All measurements were performed in accordance with the Declaration of Helsinki and approved by the ethical board of the associated EU-project “BRAIN” (No. 224156).

2.3 Data Collection

EEG data was recorded from the surface of the scalp via six water-based electrodes (Twente Medical System International (TMSI), Oldenzaal, Netherlands). Electrodes were mounted according to the extended 10-20 system of electrode placement [19] at PZ, PO3, PO4, O1, OZ, O2, O9, O10 and grounded at AFZ. Shielded cables connected electrodes and the high-impedance amplifier system (Porti32, TMSI). Sampling frequency was set to 2048 Hz with a high-pass filter at 0.1 Hz. BCI2000 software (Schalk et al., 2004) was applied for data acquisition and storage. The signal processing module was implemented in the BCI2000 framework.

2.4 Signal Processing

During stimulation with a specific frequency, the power of all (eight) others is estimated simultaneously. Successful stimulation will induce a considerable power increase within the associated frequency. Assuming stimulation with a flickering frequency of f Hz, SSVEP activity measured at electrode number i can be estimated as:

$$y_i = \sum_{k=1}^{k=N_h} \left(a_{i,k} \cdot \sin\left(2\pi kft + \Phi_{i,k}\right)\right) + b(t) \qquad ,0 \le t < TS \tag{1}$$

where $b(t)$ describes the noise, TS the time segment and N_h the number of harmonics (Friman et al., 2007). Each sinusoid on each electrode has its own amplitude and phase. The nuisance signals $b(t)$ can have several origins, e.g. concurrent brain activity, breathing artefacts or environmental disturbances. To improve target frequency detection, nuisance signals have to be decreased and the envisaged SSVEP signal to be magnified. This is achieved by a linear combination of signals determined by the N_y electrodes into new channels s (Mandel et al., 2009). With N_s as the number of channels, a single channel s_l is defined by:

$$s_l(t) = \sum_{i=1}^{N_y} w_{i,l} \cdot y_i(t) \qquad ,0 \le l < N_S \tag{2}$$

Weighting factors $w_{i,l}$ of the spatial filtering are determined on basis of the Minimum Energy Combination (MEC) that has proven good performance in former applications (Allison et al., 2010; Volosyak et al., 2010). The MEC allows the combination of an arbitrary number of electrodes. The combination matrix is constantly adapted in real time to react to electrodes that may lose contact or transmit poor signals. These electrodes receive a low weighting or might even be ignored to provide a proper signal quality over time. A sliding window of two seconds ensures sufficient EEG data for the analysis.

Total power of the SSVEP frequency is estimated slightly different to the squared Discrete Fourier Transform (DFT) magnitude (Friman et al., 2007; Mandel et al., 2009). With X_k as the SSVEP model containing the sine and cosine pairs with the harmonic frequencies, the power in the kth SSVEP harmonic frequency in the lth channel signal s_l, is estimated to:

$$\hat{P}_{k,l} = \left\| X_k^{\,T} \cdot s_l \right\|^2 \tag{3}$$

Last step of signal processing is the normalization of the absolute SSVEP activity for each stimulation frequency (which is the average of the power over all N_s spatially filtered components and all N_h SSVEP harmonic frequencies) into relative values in order to yield comparability (Volosyak et al., 2010):

$$p_i = \frac{\hat{P}_i}{\sum_{j=1}^{N_f} \hat{P}_j} \tag{4}$$

$$\sum_{i=1}^{N_f} p_i = 1 \tag{5}$$

SNR is calculated for each frequency f. The normalized and averaged SSVEP signal of a frequency during stimulation is divided by the noise signal. Here, the normalized (4) and averaged signal of a target frequency obtained during the LED-off phase is considered as noise.

$$SNR_f = \frac{\bar{p}_{f,on}}{\bar{p}_{f,off}} \tag{6}$$

The higher the SNR for a frequency, the higher the difference between SSVEP activity during the LED-on phase compared to the LED-off phase.

2.5 Statistical Analysis

A Kolmogorov-Smirnov test revealed that the data is not well modeled by a normal distribution. We applied an analysis of variance by ranks for dependent measures according to Friedman to compute differences of SNRs between all frequencies. During signed-rank tests, alpha level accumulates and Bonferroni method was applied for correction (adjusted alpha level: 0.0014). To determine effect sizes, we used the Pearson correlation (r) on basis of z-values of the Wilcoxon tests (r= z/square root(n)), (n= 126 observations).

3 RESULTS

The non-parametric Friedman test revealed considerable differences among SNRs elicited by all nine stimulation frequencies (χ^2=434,76; *p*< .001). Averaged across sessions, IPS on basis of 32 and 40 Hz induced significant higher SNRs compared to all other frequencies (*p*< .001). Also, IPS with 32 Hz elicited stronger SSVEP compared to stimulation with 40 Hz (z= -4,40; *p*< .001) (figure 2). Differences between 32 Hz and all other frequencies (except 40 Hz) amount to r=0.86, indicating large effects with regard to Cohen's benchmark. Between 40 Hz and adjacent frequencies (except 32 Hz), effect sizes amount to r=0.83.

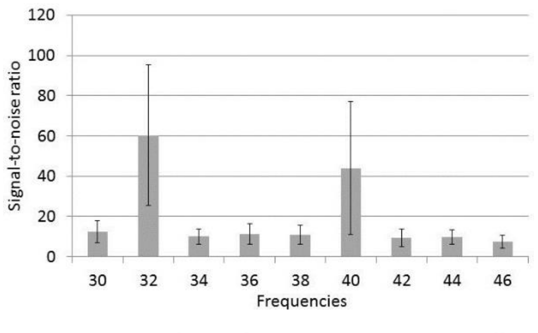

Figure 2: Averaged signal-to-noise ratios across all IPS trials.

In 92% of all cases (four LED-on periods per session for each frequency), 32 Hz proved to induce strongest or at least second strongest cortical reactions. 40 Hz turned out to be the dominant or second dominant resonance frequency during 68% of all cases. The remaining frequencies only sporadically provoked stronger responses compared to all others. Stable SSVEPs beyond 32 and 40 HZ could not be observed across the testing sessions

Figure 3 depicts the SSVEP power across time for IPS with 32 and 40 Hz as well as for two adjacent frequencies (30 and 42 Hz). For reasons of clarity, results of only ten participants are depicted (averaged across all sessions). Power was calculated simultaneously for all nine frequencies, proportional values of the four given frequencies are illustrated for LED-on segments (3.75 seconds, data points 0 to 30 and 40 to 70) and the in-between LED-off segment (1.25 seconds, data points 30 to 40). The spatial filter combines all signals of the electrode placement.

On average, IPS on basis of 32 and 40 Hz evokes a distinct physiological response. SSVEP activity occurs approx. one second after stimulus-onset as a linear increase in power. Peak amplitudes are observed after approx. 2.5 seconds. Subsequent to stimulus-offset, SSVEP power rapidly declines and falls back to pre-stimulus level. Relative power of a stimulation frequency may theoretically amount to 100%, given that power of all others is zero. Assuming all nine frequencies to contribute the same would result in 11.11% each. During IPS with 32 Hz, its specific share increases to approx. 65% of the overall activity; IPS on basis of 40 Hz reaches approx. 40% of the total power. In contrast, stimulation with adjacent frequencies (here: 30 and 42 Hz) induces no considerable SSVEP; on average, their respective share in the overall signal remains the same as during LED-off phases.

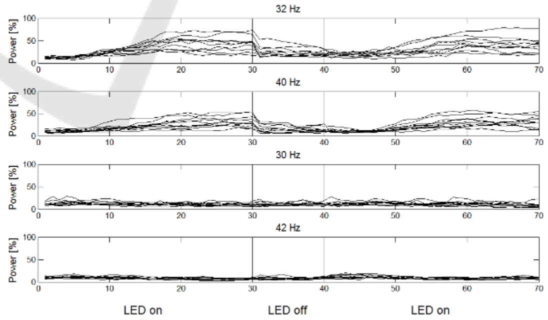

Figure 3: SSVEP power characteristics during IPS with 30, 32, 40 and 42 Hz. Individual averages of ten participants across seven runs. Abscissa: data points.

Due to differences in methods, procedure and equipment, findings from the clinical pilot study are not directly comparable to the above-mentioned results. However, cortical reactions to IPS with 32 and 40 Hz are still depicted to provide an impression on their resonance properties also in neurological patients and less controlled environments (figure 4).

Averaged across all four LED-on periods, we observe a linear increase in 32 Hz power for over three quarters of all participants; again, SSVEP activity during stimulation with 40 Hz occurs comparably less pronounced. Latencies to stimulus-onset are similar to the sample of heathy participants. However, due to the lack of comparability and the low amount of data, we refrain from general statements or inferential statistical analysis.

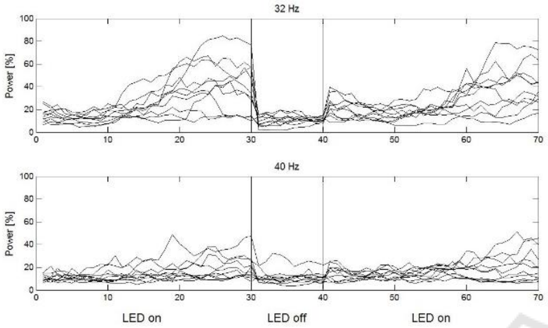

Figure 4: SSVEP power characteristics during IPS with 32 and 40 Hz for the clinical sample. Individual averages of ten participants across two runs. Abscissa: data points.

4 CONCLUSIONS

IPS above 30 Hz largely diminishes the risk of photosensitivity and reduces visual annoyance. However, BCIs that apply high frequency stimulation usually lack adequate accuracy rates and processing speed due to low signal-to-noise ratios and random subsets of frequencies (Ehlers et al., 2012). In a recent study, Chabuda et al (2018) utilize IPS between 30 and 39 Hz and observe strong SSVEP in eight out of ten frequencies for more than half of their participants. However, no specific resonance frequency emerged particularly common, indicating high interindividual differences with regard to cortical resonance above 30 Hz. Presupposing this, it would be necessary to apply time-consuming calibration phases for each individual prior to BCI use. Also, it’s not clear whether a once-identified individual frequency set will provide the same resonance performance during repeated usage. The current study aims to determine resonance frequencies above 30 Hz that produce stable and recurring SSVEP. Similar to findings during IPS featuring low (Jin et al., 2000; Ehlers et al., 2012) and high frequency stimulation (Chabuda et al., 2018), we assume cortical responses to occur selectively and to exhibit interindividual differences.

The current findings indicate that except for 32 and 40 Hz, none of the considered stimulation frequencies (30, 34, 36, 38, 42, 44, 46 Hz) repeatedly induce stable cortical responses. Though all of them occasionally produce strong SSVEP compared to adjacent frequencies, individual resonance profiles for regular BCI usage could not be defined. IPS on basis of 32 and 40 Hz, however, induced pronounced and recurring SSVEP in all participants and in the vast majorities of trials. Also, although not validated yet, results seem to be transferable to participants featuring various neurological diseases. For these users it is of particular importance to be equipped with reliable and high-performing systems. Further research on clinical users need to be carried out to evaluate whether the effects prevail in longer-term studies and may ensure adequate usage in future scenarios, for example in the area of smart homes or rehabilitation robotics.

Considering neurophysiological research over the recent past, strong reactions to flickering stimuli of 40 Hz are hardly surprising. 40 Hz oscillations are assumed to play a significant role in cognitive functions, including (but not limited to) visual feature binding (Busch et al., 2004; Basar et al., 2016) or attention processing (Herrmann et al., 1999). The disposition to external stimulation could therefore be considered as an indication that a particular frequency plays a decisive role in cognitive processing. Similar correlations have been reported for oscillations near a dominant resonance frequency in the alpha range (Pastor et al., 2003; Ehlers et al., 2012). Given that IPS identifies neuronal oscillators, synchronized responses to stimulation with 32 Hz may also suggest functional relevance of this particular frequency. While adjacent frequencies display no or only few distinct physiological responses, 32 Hz exhibits even stronger resonance properties compared to stimulation with 40 Hz. Re-test stability across various sessions at different times of day suggests that factors like vigilance, biorhythm or any kind of psychological state have little or no effect on the resonance properties. However, at this point, we cannot make any assumptions of a certain role of 32 Hz oscillations in cognitive processing.

High frequency SSVEP-based BCIs of the recent past suggest a four- or five-way command interface, allocating each stimulation frequency to a different command, e.g. “up”, “down”, “left”, “right” and “select” for screen-based spelling applications (Ehlers et al., 2012; Chabuda et al., 2018). As indicated above, these systems entail considerably lower accuracy rates/information transfer rates compared to BCIs that apply the same number of stimulation frequencies (or even more) in the range between 13 and 17 Hz (Allison et al., 2010; Ehlers et al., 2012; Stawicki et al., 2018). Individual frequency sets that may improve processing accuracy of high frequency SSVEP BCIs could not be established during this study. However, it is to be noted that we excluded numerous frequencies from our screening (31, 33, 35, 37, 39, 41, 43, 45 Hz) due to the overall duration of a session. Considering the selectivity of cortical responses to IPS, it cannot be ruled out to identify further resonance frequencies above 30 Hz. Due to only two stable and recurring resonance frequencies so far (32 & 40 Hz), high frequency based BCI usage will continue to presuppose individual calibration beforehand. However, for multimodal interaction concepts that include various physiological input options (e.g. eye movements), the application of 32 and 40 Hz stimulation may provide a further promising communication channel.

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REFERENCES

Allison, B., Luth, T., Valbuena, D., Teymourian, A., Volosyak, I. and Graser, A. (2010). BCI Demographics: How Many (and What Kinds of) People Can Use an SSVEP BCI? *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 18(2), pp.107-116.

Başar, E., Emek-Savaş, D., Güntekin, B. and Yener, G. (2016). Delay of cognitive gamma responses in Alzheimer's disease. *NeuroImage: Clinical*, 11, pp.106-115.

Busch, N., Debener, S., Kranczioch, C., Engel, A. and Herrmann, C. (2004). Size matters: effects of stimulus size, duration and eccentricity on the visual gamma-band response. *Clinical Neurophysiology*, 115(8), pp.1810-1820.

Chabuda, A., Durka, P. and Zygierewicz, J. (2018). High Frequency SSVEP-BCI With Hardware Stimuli Control and Phase-Synchronized Comb Filter. *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, 26(2), pp.344-352.

Chatrian, G., Lettich, E. and Nelson, P. (1985). Ten Percent Electrode System for Topographic Studies of Spontaneous and Evoked EEG Activities. *American Journal of EEG Technology*, 25(2), pp.83-92.

Ehlers, J., Valbuena, D., Stiller, A. and Gräser, A. (2012). Age-Specific Mechanisms in an SSVEP-Based BCI Scenario: Evidences from Spontaneous Rhythms and Neuronal Oscillators. *Computational Intelligence and Neuroscience*, pp.1-9.

Friman, O., Luth, T., Volosyak, I. and Gräser, A. (2007). Spelling with steady-state visual evoked potentials. In Neural Engineering, 2007. CNE'07. *3rd International IEEE/EMBS Conference on IEEE*, pp.354-357.

Herrmann, C. (2001). Human EEG responses to 1-100 Hz flicker: resonance phenomena in visual cortex and their potential correlation to cognitive phenomena. *Experimental Brain Research*, 137(3-4), pp.346-353.

Herrmann, C., Mecklinger, A. and Pfeifer, E. (1999). Gamma responses and ERPs in a visual classification task. *Clinical Neurophysiology*, 110(4), pp.636-642.

Jin, Y., Castellanos, A., Solis, E. and Potkin, S. (2000). EEG Resonant Responses in Schizophrenia: a Photic Driving Study with Improved Harmonic Resolution. *Schizophrenia Research*, 44(3), pp.213-220.

Mandel, C., Lüth, T., Laue, T., Röfer, T., Gräser, A. and Krieg-Brückner, B. (2009). Navigating a smart wheelchair with a brain-computer interface interpreting steady-state visual evoked potentials. *Intelligent Robots and Systems, 2009. IROS 2009. IEEE/RSJ International Conference on IEEE*, pp. 1118-1125.

Makeig, S. (2002). Dynamic Brain Sources of Visual Evoked Responses. Science, 295(5555), pp.690-694.

Molina, G. G., Ibanez, D., Mihajlović, V. and Chestakov, D. (2009). Detection of high frequency steady state visual evoked potentials for brain-computer interfaces. *17th European Signal Processing Conference. IEEE*, pp. 646-650.

Müller, S. M. T., Diez, P. F., Bastos-Filho, T. F., Sarcinelli-Filho, M., Mut, V., Laciar, E. and Avila, E. (2015). Robotic wheelchair commanded by people with disabilities using low/high-frequency ssvep-based BCI. *World Congress on Medical Physics and Biomedical Engineering*, pp. 1177-1180.

Pastor, M., Artieda, J., Arbizu, J., Valencia, M. and Masdeu, J. (2003). Human Cerebral Activation during Steady-State Visual-Evoked Responses. *The Journal of Neuroscience*, 23(37), pp.11621-11627.

Schalk, G., McFarland, D., Hinterberger, T., Birbaumer, N. and Wolpaw, J. (2004). BCI2000: A General-Purpose Brain-Computer Interface (BCI) System. *IEEE Transactions on Biomedical Engineering*, 51(6), pp.1034-1043.

Stawicki, P., Gembler, F. and Volosyak, I. (2016). Driving a Semiautonomous Mobile Robotic Car Controlled by an SSVEP-Based BCI. *Computational Intelligence and Neuroscience*, 2016, pp.1-14.

Volosyak, I., Valbuena, D., Malechka, T., Peuscher, J. and Gräser, A. (2010). Brain–computer interface using water-based electrodes. *Journal of Neural Engineering*, 7(6), p.066007.

Ware, M. P., McCullagh, P. J., McRoberts, A., Lightbody, G., Nugent, C., McAllister, G. and Martin, S. (2010). Contrasting levels of accuracy in command interaction sequences for a domestic brain-computer interface using SSVEP. *Biomedical Engineering Conference (CIBEC)*, pp. 150-153.