Effects of Stimulation Properties in Steady-State Visual Evoked Potential Based Brain-Computer Interfaces

Jordi Bieger[1,2] Gary Garcia-Molina[1] Danhua Zhu[1,3]

***Abstract*— Brain-Computer Interfaces (BCIs) enable people to control appliances without involving the normal output pathways of peripheral nerves and muscles. A particularly promising type of BCI is based on the Steady-State Visual Evoked Potential (SSVEP). Users can select commands by focusing on visual stimuli that alternate appearance with a certain frequency. The properties of these stimuli, such as size and color, as well as the device they are rendered on, can significantly affect the performance, comfort and safety of the system. However, the choice of stimulation properties is often ad-hoc or copied. In this paper we report our findings about the effects of rendering device, refresh rate, environmental illumination, contrast, color, spatial frequency and size of visual stimuli. In order to investigate these effects online, a high-performance BCI was developed. User comfort was measured using a questionnaire. The results suggest that high contrast stimulation works the best, while also being the least comfortable. However, maximum black/white contrast is often not needed and other stimuli (e.g. blue/green stimulation) are shown to work almost as well, while being far more comfortable. Knowledge of these effects can help to improve SSVEP-based BCIs.**

I. INTRODUCTION

The steady state visual evoked potential (SSVEP) refers to the response of the cerebral cortex to repetitive visual stimuli (RVSi) oscillating at a constant frequency. The SSVEP manifests as an oscillatory component in the electroencephalogram (EEG) having the same frequency (and/or harmonics) as the RVS [1]. Because of their proximity to the visual cortex, the occipital sites exhibit a higher SSVEP response.

The SSVEP is an effective electrophysiological source that can be used as input for brain-computer interfaces (BCIs). An SSVEP-based presents the subject with a set of RVSi that in general oscillate at different frequencies from each other. The SSVEP corresponding to the RVS on which the subject focuses their attention is more prominent and can be detected in the ongoing EEG. Each RVS is associated with an action which is executed by the BCI system when the corresponding SSVEP is detected.

SSVEP-based BCIs offer two main advantages over BCIs based on other electrophysiological sources (e.g. P300, ERD/ERS): 1) they have higher information transfer rate, and 2) they require shorter calibration time. Unfortunately, the constant flicker can induce visual fatigue and even epileptic seizures in those that are susceptible.

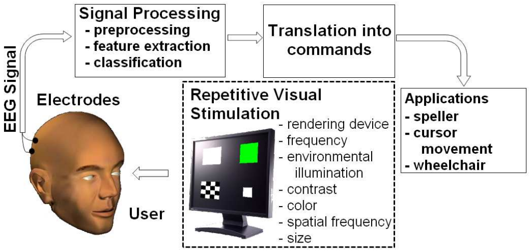


Fig. 1: Functional model of an SSVEP-based BCI.

The functional model of a BCI system is depicted in Fig. 1. The visual stimulation plays a key role in the system and has many different properties. A BCI's performance is usually determined by the information transfer rate (ITR), which indicates how much information can be communicated in one minute. Since these systems are often used for extended periods of time, it is important to consider comfort and safety as well. In order to improve BCIs, research has generally focused on signal processing techniques [2], but these do not affect comfort and safety. Stimulation properties, like color and size of the stimulus, have received fairly little attention in the context of brain-computer interfacing even though they can have a great impact on the performance, comfort and safety of BCI systems.

In this paper we present a study investigating the effects on both comfort and performance of an SSVEP-based BCI of stimulation device and its refresh rate, environmental illumination, RVS contrast, color, spatial frequency and size. Section II introduces the most relevant stimulation properties and the conditions tested in our experiments. Section III describes our BCI implementation and the protocol that was used in our experiments. Section IV discusses each of the tested properties and the results we found in our experiments. The article is concluded in Section V.

II. STIMULATION PROPERTIES AND EXPERIMENTAL CONDITIONS

When designing an SSVEP-based BCI several choices need to be made about the properties of the RVSi that the system will use to elicit an SSVEP response. In this section, we introduce the RVS properties that are tested in this study (see Fig. 2 for examples).

a) Stimulation device: An important factor that influences both comfort and performance is the device that renders the RVS. The two obvious candidates are lights/lamps and computer monitors. Computer monitor stimulation has the advantage that monitors are ubiquitous and can be easily integrated in a computer-based system. In CRT monitors there is a constant flicker at the refresh rate that may elicit an unwanted SSVEP response [3]. LCD screens do not have this problem but often have lower contrast and refresh rates. It has

1. Philips Research, 5656 AE Eindhoven, The Netherlands
2. Radboud University, 6525 HR Nijmegen, The Netherlands
3. Zhejiang University, 310027 Hangzhou, China
Please direct all correspondence to `jbieger@gmail.com`

been suggested that LEDs elicit stronger SSVEP responses than computer monitors do [3].

Specialized hardware can be used to accurately control lamps such as LEDs. This setup is less flexible and not as readily available, but the advantage is that LEDs can often be much brighter and can display frequencies accurately.

The differences between these devices are tested using green LEDs and LCD and CRT monitors with green squares of approximately the same size and brightness. This ensures that the conditions are comparable.

b) Frequency: SSVEP-Based BCIs generally use frequency as the discriminating characteristic for determining which target RVS receives the user's focus of attention. Therefore, a system with N targets needs to use N different frequencies that are sufficiently different, so that they can be distinguished from each other in the signal processing phase. The effects of frequency ranges on performance has already been studied repeatedly and will not be a part of our investigation. High frequencies are more comfortable and safer than low frequencies, but elicit a smaller response and may not be generated by some devices, specifically most computer monitors [4].

Computer monitors have refresh rates that determine which frequencies can be displayed accurately. A device with a refresh rate R can accurately render the set of frequencies R/k, where k is any integer larger than 2. Other frequencies can only be approximately rendered. It has been shown that using frequencies that the monitor can accurately render, can greatly increase performance [5]. However, this research used two different sets of frequencies for the tested conditions. In order to exclude the specific frequencies as the source of the difference, we took two sets of frequencies that were optimized for two different refresh rates: $\{18\frac{3}{4}, 15, 12\frac{1}{2}, 10\frac{5}{7}\}$ for 75 Hz and $\{15, 12, 10, 8\frac{4}{7}\}$ for 60 Hz. We then tested both sets with both refresh rates to evaluate the effect on system performance.

To optimally evaluate the effects of other properties a frequency selection procedure was used to determine the best stimulation frequencies for each subject.

c) Environmental illumination: Illuminated environments are more natural and convenient, but in the dark a bright stimulus can seem much more pronounced. The notion of environmental illumination is closely related to the contrast of the displayed RVSi (see the next paragraph). Pupil dilations caused by a dark environment might cause the eye to catch more of the stimuli's light. Furthermore, external light sources might also flicker a little, interfering with the SSVEP response. All of these observations suggest that BCI performance might be increased in dark environments [6].

d) Contrast: The contrast or "modulation depth" is defined as $(l_{\max} - l_{\min})/(l_{\max} + l_{\min}) \times 100\%$, where $l_{\min}$, $l_{\max}$ are the minimum and maximum luminance, respectively. It was shown that a higher contrast leads to stronger SSVEP responses, especially for dark-on-bright stimuli [7]. It seems intuitive however, that higher contrast also leads to lower comfort. We investigated this aspect by using different shades of gray in both the fore- and the background of our system.

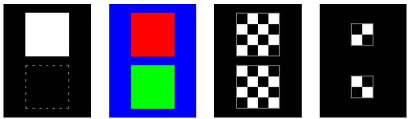

(a) w/k (b) r-g/b (c) 6cm4x4 (d) 3cm2x2

Fig. 2: Examples of stimulation properties showing both states of a condition and the background color. (a) white-on-black stimulation and (b) red/green stimulation on a blue background. (c) and (d) checkerboard stimulation with the same spatial frequency of 0.8 alternations/degree, but different sizes.

e) Color: It is well known that color can affect mood as well as SSVEP response [1]. We tested combinations of the primary colors red, green and blue. In the more perceptually relevant color space that is described in terms of hue, saturation and lightness, these colors only differ in hue. However, device specificities might cause these values to be inaccurate.

f) Spatial frequency: Checkerboards are often used as an alternative to single graphic RVSi. Using checkerboards elicits an SSVEP at twice the stimulating frequency. Some studies have found that better brain responses are elicited this way [8], while others have found the contrary [9]. The spatial frequency is determined by the size and the number of cells of the stimulus. We tested powers of two for the number of cells in both dimensions as well as a checkerboard with cells consisting of 4x4 pixels (54x54 cells).

g) Size: The larger the stimulus, the easier it is to notice, but the harder it is to ignore. Stimulus size also affects the amount of light transmitted to the user and determines how large an application needs to be or how much surface area remains for other purposes.

III. EXPERIMENTAL SETUP

Seven experiments were conducted where the subject had to control a custom made BCI. We tested the effects of (1) rendering device, (2) stimulation frequency vs. refresh rate, (3) environmental illumination, (4) contrast, (5) color, (6) spatial frequency and (7) size. Ten people participated (7 men and 3 women) in several experiments in such a way that there were six different subjects for each experiment. The participants were aged between 24 and 32 and had normal or corrected to normal vision. They were seated comfortably at approximately 70 cm distance from the stimulation device and hooked up to the BioSemi ActiveTwo EEG acquisition system [10]. Electrodes were placed in 32 positions according to the international 10-20 system, but only 8 electrodes over the occipital region (visual cortex) were re-referenced to Cz and used by the system. Unless specified otherwise, the experiments were carried out using an LCD with a refresh rate of 75 Hz in a dark room and white flickering square stimuli of 6x6 cm on a black background. Each condition or experiment varied something about this default configuration.

Before the last four experiments the user was asked to complete an empirically designed questionnaire where they indicated how pleasant, tiring and annoying each condition was and how long they could look at it on 7-point scales. Their answers were averaged into one comfort score where 1 indicates low comfort and 7 indicates high comfort. The questionnaire was conducted before the experiment in order

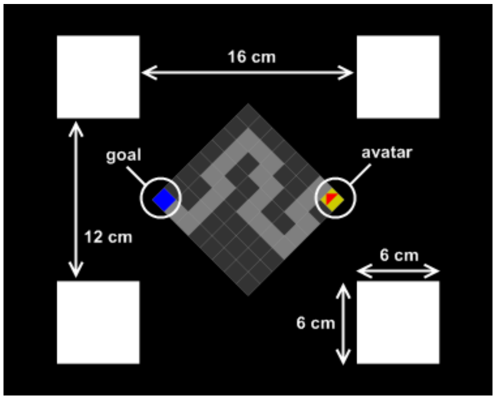


Fig. 3: The interface of the BCI used for experimentation. The user can move the avatar to the goal by focusing on the white flickering targets associated with the desired directions.

to minimize the effect that performance might have on the answers. A 3 minute long frequency selection process was conducted in order to select the frequencies that worked best for each individual subject. For every condition, a 3 minute long calibration phase preceded operation of the BCI.

The user had to move an avatar (red triangle) along a curvy corridor to a goal (see Figure 3). There were no bifurcations, so there was only one way to move through the corridor.

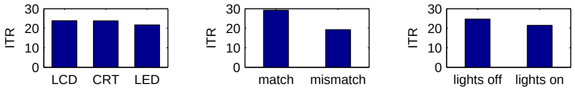
The user could move the avatar by focusing on the target associated with the intended direction. When the system classifies the resulting brain signals, the avatar turns towards the signified direction and tries to move there. If the avatar is blocked by a wall, it will not change position. Correct moves are accompanied by a green screen flash and a high pitched tone and bad moves by a red flash and a low pitched tone. Each move was followed by a one second period of inactivity in order to provide the user with enough time to change his focus and for the SSVEP response to diminish.

For each condition there were two corridors of 24 steps. The subject could attempt to finish each corridor in three blocks of one minute separated by 20-second pauses, which were given in order to prevent fatigue and frustration.

The system estimates the power in the EEG signal of the frequencies (and harmonics) associated with the targets. The signal is first preprocessed using a 50 Hz IIR notching comb filter in order to remove the power line interference. The power for a target is then calculated by applying a maximum contrast spatial filter [11] for the first 4 harmonics of the target frequency. The result for each harmonic is peak filtered, squared and averaged over the last second. The sum of the powers of the harmonics is then used for classification. If the power for exactly one target exceeds the associated threshold, the system moves the avatar in the corresponding direction. After the calibration and frequency selection phases, suitable spatial filters, thresholds and frequencies are determined according to the procedure in [4].

IV. RESULTS AND DISCUSSION

BCI systems are usually evaluated in terms of information transfer rate (ITR) or bitrate, which is measured in bits/minute. This number can easily be calculated by dividing the number of communicated bits by the duration of the task in minutes. In addition to the bitrate, we also consider the comfort of the system on a 7-point scale ranging from low to high comfort, based on the subjective observations of the subjects before the experiments.



(a) stimulation devices (b) refresh rate (c) lighting

Fig. 4: ITRs for the stimulation devices, refresh rate optimization and illumination environment experiments.

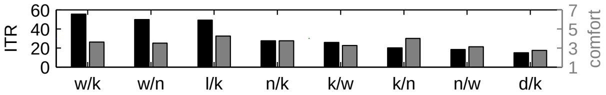
There was high inter subject variability in terms of overall performance. Different users may also respond differently to each of the conditions, but one pattern clearly emerges: more pronounced changes between stimulus states result in both better performance and lower comfort (Fig. 5). In addition to leading to low performance, bright backgrounds were judged as uncomfortable.

However, some compromises can be made to make the system more comfortable without significantly sacrificing performance. The tradeoff is visualized in Fig. 6. We have defined four quadrants where the comfort and ITR axes were (arbitrarily) divided at their middle point. The top right quadrant corresponds to good comfort and high performance (ITRs above 30 bits/min can be considered as high for BCIs [4]). Using (light) gray, blue or green/blue stimulation can give high average ITRs. Green/blue alternating squares on a black background provide the best tradeoff between comfort and performance.

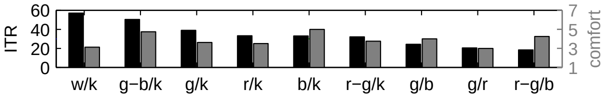
We tested whether the stimulation device itself has any effect on BCI performance. Results from the literature suggesting that LEDs elicit stronger responses than LCDs and CRTs were not confirmed and it was found that there was virtually no difference (Fig. 4a). The results also show that matching the chosen frequencies to the used refresh rate improves performance (Fig. 4b). However, optimizing the used frequencies for the user rather than the rendering device may give even better results. A dark environment is shown to be slightly more advantageous (Fig. 4c), confirming the results from [6]. Although no questionnaire was conducted, subjects did comment that they preferred the more natural condition where the lights were on.

We found that contrast is indeed positively correlated with performance, but only for bright-on-dark stimuli (Fig. 5a), contrary to the results form [7]. Bright backgrounds were also judged as uncomfortable.

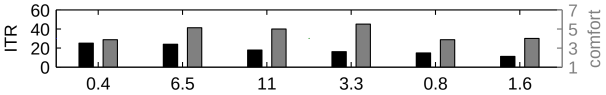
Color can indeed have a big impact on both comfort and performance (Fig. 5b). Again, bright (colored) backgrounds do not seem like a viable option. Green stimuli appear to work the best, which can be explained either by the fact that the human eye is the most sensitive to that color, or that green's brightness is higher than that of red and blue. Alternating green/blue stimulation seems to work exceptionally well, suggesting that alternating between hues can indeed give better results, especially given that the comfort level of this stimulus was high. Alternating red/green stimulation does not work nearly as well, but this can be explained by Hering's color opponency theory which states that red and



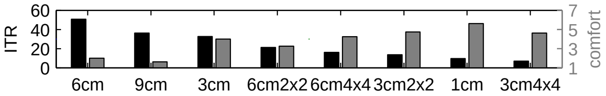
(a) contrast



(b) colors



(c) spatial frequency (in alternations/degree)



(d) sizes

Fig. 5: Performance (dark bars) and comfort (light bars) scores. The conditions are listed in descending order of performance. Colors are referred to by these letters: **r**ed, **g**reen, **b**lue, blac**k**, **w**hite, and **l**ight, **d**ark and **n**eutral gray. The label ‘r-g/k’ means that the stimulus was alternating between red and green on a black background, ‘w/n’ means that a white stimulus was popping out of a neutral gray background.

green (and yellow and blue) can cancel each other out.

Our results show that using higher spatial frequencies (and thus smaller cells) can sometimes be beneficial (Fig. 5c). However, the relationship with performance appears to be nonlinear and strongly subject dependent. User comfort is clearly positively related with the spatial frequency, which is likely due to the smaller cell sizes. Using a spatial frequency of 6.5 alternations/degree appears to provide the best tradeoff. However, the performance is worse than that achieved in most of the single graphic conditions. This observation that single graphics outperform checkerboards is confirmed by Fig. 5d.

The size of the stimulus seems to have a negative effect on user comfort for both checkerboards and single graphics (Fig. 5d). BCI performance was more positively impacted by an increase in stimulus size. However, when the BCI used the largest tested stimulus (9x9 cm; $7°21'23''$), performance was lower than when 6x6 cm ($4°54'29''$) were used.

The simplest explanation is that there is an optimal stimulus size that makes up a relatively small area of the visual field. A more likely explanation is that making the non-target stimuli larger and closer to the one the subject was attending to, had a detrimental effect on performance. This could be either due to increased interference in the eye, or increased difficulty to focus on the desired target. More experiments have to be carried out to investigate the cause of this anomaly.

V. CONCLUSION

Both performance and comfort vary in a broad range depending on the RVS properties. Our experiments show that comfortable conditions usually lead to low performance and that high performing conditions are often uncomfortable. Few settings combine high performance with relatively good comfort (top right quadrant in Fig. 6), but light gray, blue and green-blue stimulation provide a good tradeoff.

It is important to balance comfort and performance, especially if the system is used for extended periods of time.

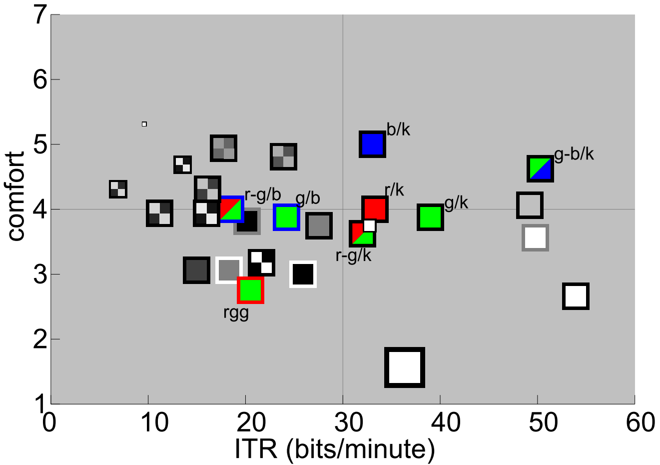


Fig. 6: Visualization of the results where each point depicts a condition and its position shows its ITR and comfort. The edge of each point shows the background color and the face shows the stimulus. If the stimulus alternated between two colors, both are depicted as triangles. For the checkerboards, a small checkerboard is shown where the contrast of the color is correlated with the spatial frequency. Colored RVSi are labeled because this paper is in black and white.

Our study shows that stimulation conditions exist that offer better comfort at the cost of minor decrease in performance.

Additional properties that are worth investigating are spatial and temporal blur, shape and general stimulus appearance. Furthermore, interactions between properties may not be linear, so different combinations need to be tested.

VI. ACKNOWLEDGMENTS

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