

SSVEP at single and beating frequencies utilizing perceptual insights

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Abstract: Steady state visual evoked potentials (SSVEP) are widely used in EEG research as they offer a relatively high signal to noise ratio allowing the investigation of visual processing at the cortical level. When the eyes are presented with a flickering stimulus (up to $\sim 100\text{Hz}$), the visual cortex generates a response oscillating at the same fundamental frequency as the stimulus. For research purposes, these stimuli always had the goal of eliciting a sufficiently strong EEG response. As a negative result, these stimuli are annoying to most users and even become dangerous in regard to photosensitive epilepsy. Results from psychophysical research were used to generate flickering stimuli which are around the human perception threshold for flickering lights. It is shown for multiple frequencies that eliciting an SSVEP response with stimuli below the perception threshold is possible. The human sensitivity to low frequency flicker makes it difficult to elicit an SSVEP response around the perception threshold. Therefore, we tried generating waves combining two higher frequencies and using the non-linearity of the human visual system to generate a sub-harmonic beating frequency. We attempted to elicit an 8Hz response by using the sum wave of $n*8\text{Hz}$ and $(n+1)*8\text{Hz}$ (where n is a positive integer).

1 INTRODUCTION

A widely used method to study neurophysiological processes in the brain consists of monitoring the response of the brain to flickering stimuli (Regan, 1977). When repetitive visual stimuli (RVS) are used, in the frequency range of approximately 5Hz to 100Hz they can elicit a steady state visually evoked potential (SSVEP) (Herrmann, 2001). This SSVEP can be recorded on the scalp as an oscillatory response having the same fundamental frequency as the driving stimulus. Measuring of these signals on the scalp can be done by means of an electroencephalography (EEG). The SSVEP signal is most prominent in the parietal and occipital lobes of the brain, as they are close to the primary visual cortex (Regan, 1989).

Apart from research into neurophysiological processing, stimulating the brain with flickering light stimuli has several other applications. One such application is using light for brain wave entrainment. Light has been proven to affect cognitive functioning both via its role as provider of visual information as well as its direct activating effects (bright light, oscillating light) (Marshall et al., 2006; Bieger and

Garcia Molina, 2010). For instance, the use of RVS to increase working memory performance has been proven in previous research (Perlstein, 2003; Ellis et al., 2006). Furthermore, the relatively high signal to noise ratio of the SSVEP signal in EEG measurement makes this an often used method for brain computer interfaces (BCI) (Allison et al., 2007; Zhu et al., 2010a; Krusienski and Allison, 2008).

The widespread use of RVS also makes the shortcomings or the negative effects of these stimuli more apparent. If we look for instance at brain wave stimulation, we see that the power bands which are found to be important in working memory are relatively low. They are all in the Theta (3,5 - 7Hz), Alpha (7,5 - 12Hz) or Beta (17 - 29Hz) range (Klimesch, 1999; Tsoneva et al., 2011; Andreassi, 2007). If the RVS are presented in this range, the flickering of the stimulus is very noticeable. Stimuli oscillating at frequencies under 25Hz have a higher probability of causing visual fatigue and risk of epileptic seizure compared to oscillations at higher frequencies (Fisher et al., 2005). In BCI experiments using RVS, users often complain about annoying or distracting stimuli, even if these stimuli are at a much higher flicker frequency,

users complain about headache and eye strain (Allison, 2010). So in general there are clear disadvantages in using RVS. However, significant psychophysical research has been done on human perception of flickering light. Unfortunately little research has been done on the relation between human perception and neurophysiology of flicker (Tweel, 1964). Research into this topic could help making the RVS used in experiments more comfortable and safer. For instance to make the stimuli in BCI experiments less annoying to look at for the user and perhaps also to make the signals more distinguishable (Zhu et al., 2010b).

1.1 Perceptual Insights

Significant research has been done into the human perception and processing of flickering light. The findings in this area include the Flicker Fusion Frequency (FFF) (Simonson and Brožek, 1952) and Critical Fusion Frequency (CFF) (Levick, 1953). They both indicate a threshold for the frequency at which a person no longer perceives flicker but a continuous light. The FFF is used in many illumination applications ranging from lighting to computer and TV screens. The FFF is not a fixed parameter that is the same for every person, it varies between people and changes within a person. Things like age, concentration, fatigue and circadian rhythm are important human factors while from the stimulus side, the color of the stimulus, background color and intensity of the light have an influence on the perception threshold (Brožek and Keys, 1945; Green, 1969; Brindley et al., 1966; Stockman et al., 1993). The perception threshold at which the flicker is not perceived anymore is around 60Hz (Green, 1969). This explains for instance why old computer screens have a refresh rate of 60Hz. Interesting findings in the way the human visual processing system works have been made by looking at what happens to the brain when the frequency of the RVS exceeds the FFF threshold. Research has shown that even though the person does not perceive flicker, the brain still exhibits activity in the form of an SSVEP response (Herrmann, 2001; Porbadnigk et al., 2011).

1.1.1 Modulation Depth & Perception Threshold

One of the important aspects of the light with respect to the perception of flicker is the modulation depth (Kelly, 1961). The modulation depth of the flickering light is calculated by the formula given in equation 1. It is an indication of the ratio between the average light level and the amount of change in the light level. Figure 1 visualizes the concept of modulation depth which is important as the higher the modulation

depth is, the higher the perceived intensity of flicker is (Sokol and Riggs, 1971).

$$MD = \frac{(a + m) - (a - m)}{(a + m) + (a - m)} * 100, \quad (1)$$

where:

- MD = Modulation depth (in %)
- a = average luminance
- m = modulation amplitude

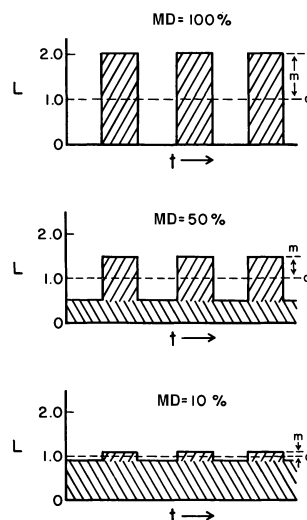


Figure 1: Fluctuation of luminance L as a function of time t displaying modulation depth of 100, 50 and 10 percent respectively, adapted from (Sokol and Riggs, 1971).

Two stimulus properties which determine the human perception of flicker are frequency and modulation depth. With these two properties it is possible to create a two dimensional flicker perception threshold, which is a curve in the 2D plane of frequency and modulation depth (Kelly, 1961). The flicker perception threshold shown in Figure 2 indicates frequency and modulation depth are not linearly related with regard to the human perception of flicker. It is clear from this figure that for low frequencies people are very sensitive to flicker, as only a small modulation depth is enough for people to perceive flicker. While for higher frequencies the perception threshold is found at a much higher modulation depth. The modulation depth of the perception threshold increases rapidly with frequencies of 40Hz and higher.

1.1.2 Beating Frequency

The use of multiple frequency stimuli (2 or more RVS at different frequencies at the same time) has been found to produce (sub-)harmonics related to combinations of the frequencies (Herrmann, 2001; Shyu

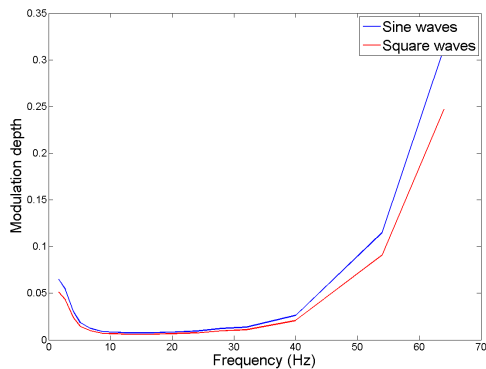


Figure 2: Flicker perception threshold as a function of frequency and modulation depth (Kelly, 1961).

et al., 2010). These (sub-harmonics) are caused by non linear processing in the brain. When each eye is presented with a different stimulus at the same time, the stimuli can either compete or combine with each other. One example of the combination of stimuli is called “binocular beats” (Baitch and Levi, 1988; Baitch and Levi, 1989). The difference in frequency between the two stimuli is called the beating frequency and can be very well perceived with the appropriate conditions (Carlson and He, 2000; Karrer, 1967). Binocular beats are the result of the spatial combination (fusion) of high frequency flicker stimulation of each eye independently. One of the problems with binocular beats is that it is not trivial to stimulate the eyes separately.

While the binocular beats are a result of spatial merging of two signals, there has also been research showing that temporal merging of signals can be found in the visual system (Shyu et al., 2010). When looking at two sources of RVS with both eyes simultaneously, the brain merges this signal temporally in such a way that (sub-)harmonics of combination frequencies can be found in the SSVEP response. This could be useful when trying to stimulate at frequencies below 40Hz, where people are very sensitive to flicker. A combination of higher frequency stimuli induce a low frequency response, with the possible benefit of stimulating at much higher modulation depth.

1.2 Goals in this Research

This project aims at connecting the psychophysical research done on the human perception of flickering lights with the neurophysiological research on SSVEP. This can help to improve design better RVS where better means more comfortable and safer. The improvement we strive for is to find RVS that are effective as well as pleasant and safe for people. This is

done by looking at what happens to the SSVEP signal when the RVS properties are around the perception threshold. Also we investigate some stimuli of which we think they would generate SSVEP signals at a beating frequency. In our experiment we use a single light source showing a complex waveform combining two frequencies, where the difference between the two frequencies is the beating frequency.

The research questions we strive to answer are:

- Can we create effective RVS which are comfortable and safe for the user?
- Can we find effective RVS around the perception threshold?
- Can we combine higher frequency stimuli into a complex waveform in such a way that the brain generates a beating frequency SSVEP?

2 METHODS

Ten volunteers (5 male, 5 female, mean age 24, SD 1.7) participated in this experiment. The participants were seated comfortably in a room where the only light came from our setup. They were facing the wall with their eyes fixed on a indicated point on the wall. The wall was illuminated evenly from above by two custom made LED luminaires with a diffusing screen in front. The LEDs were controlled through an Agilent 33522A function generator, which can generate arbitrary waveforms and is controlled through a TCP/IP interface.

To test our hypotheses we presented the participants with randomly ordered trials. Each trial had a stimulus period of 3 seconds at an average light level of 980 lux, followed by an inter stimulus interval of random duration between 3 and 7 seconds, during which DC at the same average light level of 980 lux was shown. An average epoch duration of 8 seconds with 400 trials makes the experiment last for about 54 minutes. To counter participant fatigue, we presented the experiment in 2 sessions (lasting 27 minutes) with a short break in between. This leads to an experimental timeline displayed in Figure 3. The experimental timeline was created as a Java program, as well as the TCP networking module used by MATLAB to load the waveforms into the Agilent signal generator.

The participants were presented with two different conditions: single frequency waves and combined frequency waves. For the single frequency setting, 5 different frequencies were used: 8Hz, 24Hz, 32Hz, 40Hz and 48Hz. For the combined frequency waves, sum waves were used at three different frequency combinations: 24Hz-32Hz, 32Hz-40Hz and

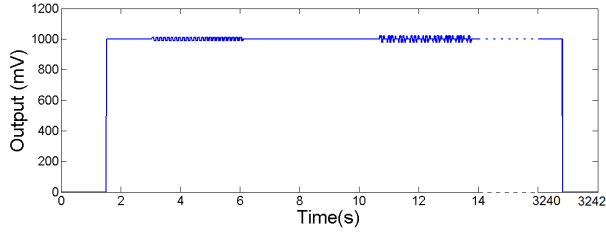


Figure 3: Flow of the experiment

40Hz-48Hz. These are all combined frequency waves of $n*8\text{Hz}$ and $(n+1)*8\text{Hz}$ (where n is 3, 4 or 5). We chose 8Hz for our beating frequency because it is right in between Theta and Alpha power bands, which were shown to be important in neural processing (Klimesch, 1999). If we show the ability to stimulate at 8Hz, this may extend to the Theta and Alpha power bands.

Each waveform was created at 5 different modulation depth settings. They were all fractions or multiples of the square wave perception threshold: 0.6, 0.8, 1.0, 1.2 and 1.4 * the perception threshold (henceforth referred to as MD6, MD8, MD10, MD12 and MD14). For the combined frequency waves, the modulation depth of the lowest frequency is used. The exact settings of the stimuli with regard to the perception curve are shown in Figure 4. These 8 waveforms times 5 modulation depth settings led to a total of 40 conditions. As EEG signals are inherently noisy there is always a trade off between signal to noise ratio and experiment duration. We chose 10 trials per condition, this improves the signal to noise ratio by a factor of $\sqrt{10} \approx 3$ and gives us a total of 400 trials.

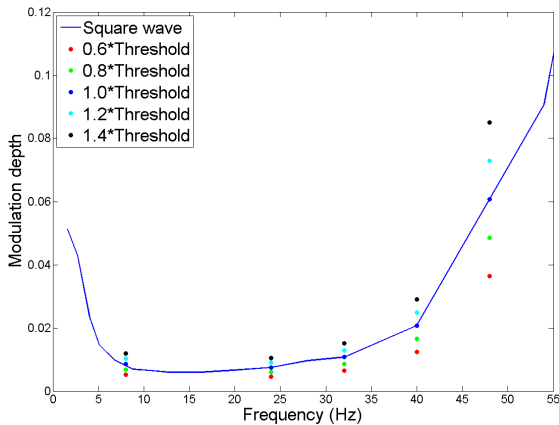


Figure 4: Absolute modulation depth of the stimuli relative to the flicker perception threshold.

2.1 Signal Acquisition and Preprocessing

During the experiment, EEG was recorded using a BioSemi ActiveTwo acquisition system at a sampling rate of 2048Hz (Biosemi,). A 32 electrode setup was used with an added common mode sense and driven right leg as “ground” electrodes (Winter and Webster, 1983). The electrodes were placed according to the international 10-20 system (Towle et al., 1993). For the recording of the data from the Biosemi acquisition device, the open source program ActiView was used (Biosemi,).

A 50Hz notch filter and a high pass filter with a cutoff frequency of 2Hz were used to reduce power line interference and baseline shift. The data was resampled to 256Hz, and independent component analysis was used to remove eye blink artifacts (Hyvärinen and Oja, 2000). Re-referencing to common average was done to improve source localization by creating an improved reference (Nunez and Srinivasan, 2006). Some further automatic artifact rejection was done to improve the signal to noise ratio.

3 RESULTS

3.1 Time Domain

To check if our stimuli elicits an SSVEP response in the brain, we calculate for all participants the signal power over time and check if there is a change in response of the brain between trial and baseline at the presented frequency during the trial. The signal power is defined as the amount of energy per time unit (see Equation 3), while energy is the sum of the squared amplitudes at each time point (see Equation 2).

$$E = \sum_{i=1}^{D \cdot R} x_i^2, \quad (2)$$

$$P = \frac{E}{D \cdot R}, \quad (3)$$

where:

- E = Energy
- R = Power
- x = signal
- i = Sample index
- D = Duration (s)
- R = Sample rate (Hz)

To be able to see a change in this power, we include the whole epoch, which includes the 3 seconds

of stimulation (henceforth called trial) and a 3 second prestimulus period as well as 1 second poststimulus. SSVEP is usually most prominent in the occipital sites of the brain in the vicinity of the primary visual cortex.

Figure 5 was created by peak filtering the data at the frequency of stimulus, calculating the power over all samples in the epoch and averaging the power over all trials in the same condition. This figure shows SSVEP signal power for one participant at one condition in one channel, in this case a 40Hz single frequency wave at MD14 in channel Oz. The power increases after the onset of the stimulus (indicated by the black line). It is also evident that with the end of the stimulus the power decreases. This response (called entrainment) is only found at the frequency of stimulation and is similar for most participants and most conditions confirming that the response we see is caused by the presented stimuli, not because of some strange artifacts. The strength of the entrainment however, differs among conditions.

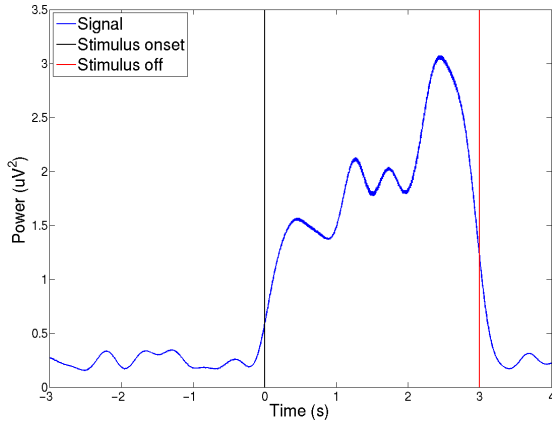


Figure 5: Average power at the frequency of stimulation of 1 participant over the trials at 1 condition in 1 channel (single frequency wave, 40Hz, MD14, channel Oz).

3.2 Frequency Domain

After looking at the signal in the time domain, we want to see in the frequency domain which frequencies get entrained by each of the stimuli we present. The Fourier transform of each trial is calculated using Welch's method (Welch, 1967), this gives the power spectrum density (PSD). We set a window length of 1 second (256 samples) and an overlap of windows of 0,5 seconds (128 samples) which gives us 5 windows in total for a 3 second long trial.

Figure 6 shows the PSD of one participant over all single frequency wave conditions at all the different modulation depths at channel Oz. The figure

shows the different modulation depths in the different columns, increasing from left to right from MD6 up to MD14 and different frequencies in the rows increasing from top to bottom from 8Hz up to 48 Hz. The vertical lines indicate the frequency of stimulation in each graph. For higher frequencies and higher modulation depth, we see a clear peak at the frequency of stimulation. For lower frequencies or modulation depth, this response is less obvious.

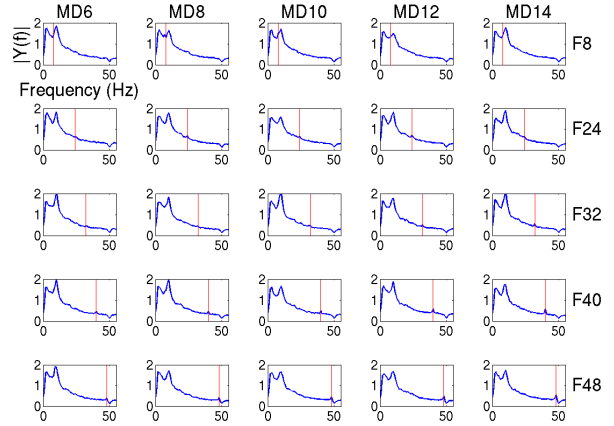


Figure 6: PSD of 1 participant over all single frequency wave conditions average over 10 trials (channel Oz). Columns show different modulation depth, rows show different frequencies

To get an objective measure of whether the peak in the signal at the stimulus is actually present in the EEG, we compare EEG signals during the stimulus with the period right before the stimulus (baseline) where the brain is in a resting state. To get this objective measure we calculate the Z-score using the formula given in equation 4. For baseline we chose the 3 seconds before the stimulus onset. This gives us a baseline averaged over 400 trials of DC light. The Z-score gives us an independent measure of the deviation of the frequency spectrum from the baseline. In essence this means that the Z-score is a measure for SSVEP signal strength. A Z-score of 2 is considered significant at the 95% level.

$$Z_{score} = \frac{x - \mu}{\sigma}, \quad (4)$$

where:

- x = frequency spectrum during the trial
- μ = frequency spectrum of the baseline
- σ = standard deviation of the baseline

Figure 7 shows the Z-scores averaged over all participants for all single frequency wave conditions at channel Oz. The layout of this figure is the same as in Figure 6 with modulation depths in the columns

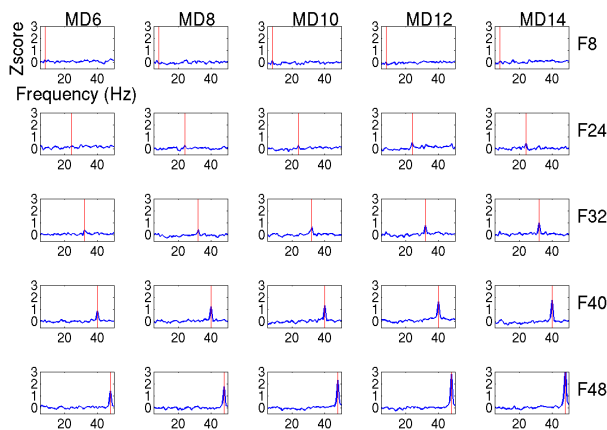


Figure 7: Average Z-score over all participants for all single frequency wave conditions (channel Oz).

and frequencies in the rows, the red line again indicating the frequency of stimulation. The SSVEP signal strength is only significant in a few conditions, however, the figure shows that with increasing modulation depth the strength of the SSVEP signal increases. Interestingly there is also a trend of increasing SSVEP signal strength with increasing frequency. The increase in signal strength with modulation depth was expected, but the increase in signal strength with frequency was not expected. As mentioned before, people are very sensitive to flicker at low frequencies. Therefore, to stimulate below the perception threshold we need very small amplitude changes in these conditions. These changes could be too small to cause a measurable SSVEP response. To further investigate the Z-score results we look at the Z-scores at the individual level.

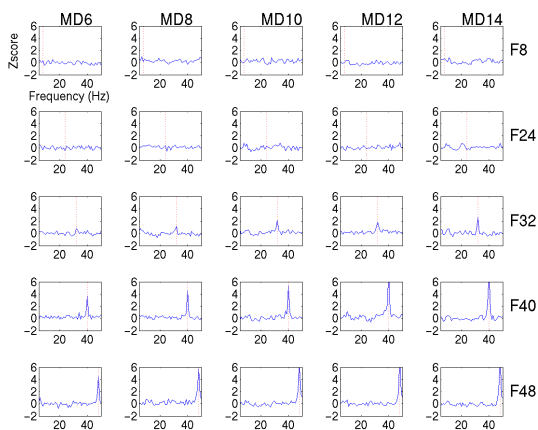


Figure 8: Average Z-score of 1 participant for all single frequency wave conditions (channel Oz).

Figure 8 shows the average Z-scores of one participant for all single frequency wave conditions at channel Oz. This figure shows that for individual partic-

ipants the Z-score shows significance for many more conditions. At the same time the same interesting increase in SSVEP signal strength with both modulation depth and frequency we see in figure 7 is also visible. The effect we see for this participant was not found for all participants. There were some participants who showed no or only a very small entrainment. The low average Z-score is due to the absence of entrainment for some participants.

To test the significance of the individual results, we used the Wilcoxon rank-sum test (Wilcoxon, 1945; Gibbons and Chakraborti, 2003; Hollander and Wolfe, 1973). With this nonparametrical statistical method the signal power in the EEG at the frequency of stimulation is compared between the trial and the prestimulus period for each participant. For this calculation we again look at the power in channel Oz.

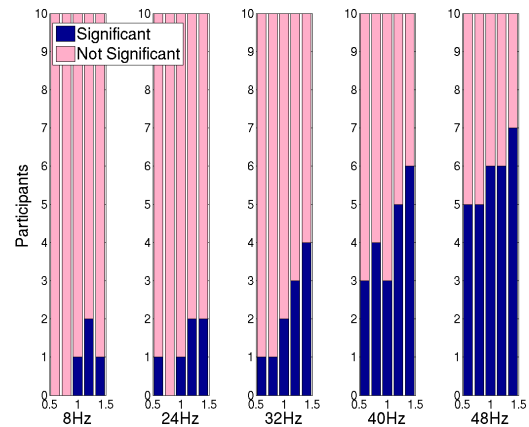


Figure 9: Number of significant results for all single frequency wave results. Different graphs show different frequencies and the bars indicate different modulation depths.

Figure 9 shows the number of participants for whom the power at the frequency of stimulation in the EEG signal during the trial was significantly larger than before the trial (at a 95% level, $p < 0.05$). The different graphs show different frequencies and for each frequency, the different bars indicate different modulation depths. The blue part indicates the number of participants with a significantly higher power during the trial than before. The red part indicates participants with no significant difference.

This figure shows that with the increase in modulation depth, the number of significant results grows. It shows a similar increase in significant results with the increase in frequency. These results reflect the increase in SSVEP signal power with both modulation depth and frequency, which is similar to the Z-score results shown before.

3.3 Spatial Distribution

To further investigate the strength and the spatial properties of the response, we analyze the spatial distribution of the SSVEP response. We plotted the Z-score at the frequency of stimulation for all channels in a topographic map (referred to as topoplot) which shows a 2D representation of the Z-score where the electrodes are displayed according to their locations on the scalp.

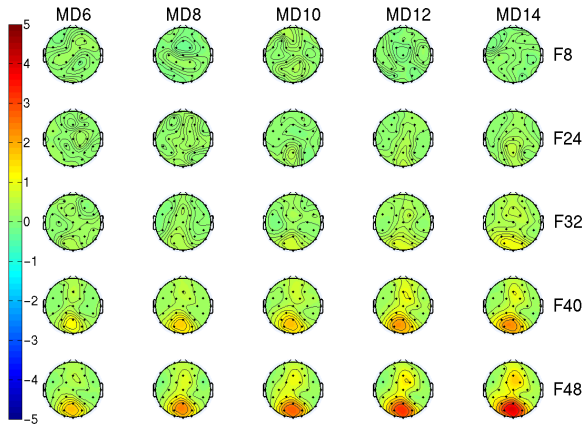


Figure 10: Average topoplots of Z-score of all participants for all single frequency wave conditions.

Figure 10 shows average Z-scores over all participants at the frequency of stimulation for all single frequency wave conditions in all channels. The figure clearly shows that the strongest SSVEP response is at the back of the head near the primary visual cortex. Furthermore, the increase in signal strength for both modulation depth and frequency is reflected in this figure. We also observe an influence of the SSVEP response at frontal sites, especially for higher modulation depth and frequency, this effect is however small.

3.4 Combined frequency waves

The analysis for the combined frequency wave trials in the experiment were conducted similarly to those for the single frequency trials. To give an overview of the results for the combined frequency waves, the Z-score plot is the most appropriate as this gives an indication of the strength of the entrainment for the different frequencies that are combined into a combined frequency wave. The rows in this plot show the combined frequency waves with the frequency on the right indicating the lowest of the two combined frequencies, F24 meaning a combination wave of 24Hz and 32Hz. The vertical lines indicate the 2 frequencies that make up the combined frequency wave as well as the 8Hz beating frequency.

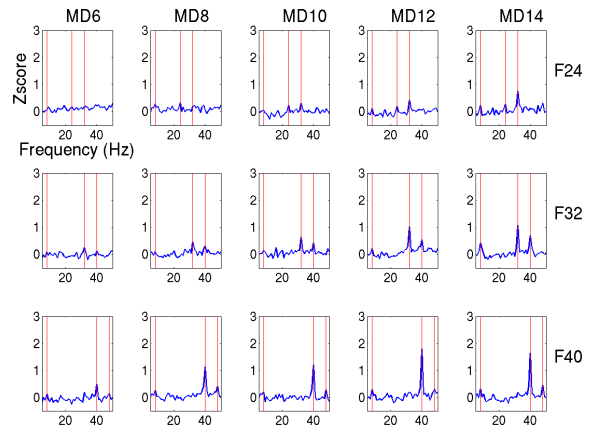


Figure 11: Average Z-score over all participants for all combined frequency wave conditions (channel Oz).

Figure 11 shows that none of the conditions result in a significant SSVEP response (with the criterium of a Z-score >2). We do, however, see a similar trend we observed in the single frequency wave condition with the signal strength increasing with both modulation depth and frequency. It also becomes clear from this figure that the entrainment at the beating frequency is very small. Furthermore, the figure shows that in the 40Hz-48Hz condition, the 40Hz entrainment is much larger than the 48Hz entrainment, which seems to contradict our earlier findings that the signal strength increases with frequency. However, the modulation depth used for these trials is based on the perception threshold at 40Hz. As figure 4 shows, the rise of the flicker perception curve at this point is very steep. The lowest absolute modulation depth at 48Hz is higher than the highest absolute modulation depth at 40Hz. This causes the 48Hz entrainment to be very small in comparison with the entrainment at 40Hz.

4 CONCLUSION

In this study, we compared the SSVEP response in human participants to a RVS in several conditions around the flicker perception threshold. Single frequency waves were used to see if it is possible to find entrainment from stimulation with light conditions around the perception threshold and combined frequency waves were used to see if entrainment at a beating frequency was possible from stimulation with a combination of higher frequencies. Our results suggest that a trade-off between SSVEP signal strength and user safety and comfort is possible. This claim is supported by the fact that we find entrainment at the stimulus frequency at modulation depths below the perception threshold. This indicates that it is in-

deed possible at least for higher frequencies to stimulate effectively below the perception threshold. Such stimulus is more comfortable for the user and safer as it will less likely induce headache and eye strain.

Another interesting finding is that both frequency and modulation depth have an effect on SSVEP signal strength. Most notable here is that the effect of frequency and modulation depth on SSVEP signal strength does not align with the perception threshold curve. This shows that the relation between perception and SSVEP signal strength changes with frequency. For low frequencies we do not see entrainment at modulation depth higher than the perception threshold while for higher frequencies we even see entrainment below the perception threshold. This both offers some insight in the human processing of RVS as well as allowing for the creation of effective RVS that are comfortable and safe for the user. However, further work is needed to get more insight into the link between perception and SSVEP.

The conclusions for the beating frequency part of the experiment are less obvious. Most of the tested conditions do not exhibit any entrainment and even when we do see some entrainment at the 8Hz beating frequency, this entrainment is not significant.

5 DISCUSSION & FUTURE WORK

As mentioned in the results, there is an unexpected increase in signal strength with frequency. We assume this has to do with the very small modulation depths in the low frequency conditions. This led to the conclusion that the SSVEP signal strength does not align with the perception threshold curve. Further investigation into this part of the research could offer insight on how the human visual processing works, as it is strange that when people do perceive flicker there is no recorded SSVEP response.

In the results it is mentioned that not all participants showed equally large entrainment. There were even participants who showed no SSVEP response at all. While this is in line with the literature (Volosyak et al., 2011; Allison et al., 2010), a very obvious next step in this research track is to look at personal perception thresholds. The threshold used in this experiment is a guideline to start from, but as mentioned before (section 1.1) there are a lot of factors determining the perception of the flicker. The perception threshold can vary between people and also within one person. Using an individual perception threshold the relation between perception and entrainment should become more obvious. An easy way to set this up is to recre-

ate this experiment asking the participants to press a button each time they perceive flicker in order to get an indication of the perceived flicker as well as the strength of the entrainment for each participant.

Also on a individual participant level, there is no indication as to how the results will influence users suffering from photosensitive epilepsy. Possible future research could be in the direction of the effects of RVS at low modulation depth on epileptic seizures. This could offer some insight into the foundations of photosensitive epilepsy.

Another question that still needs to be answered is how and when the beating frequencies occur. We do see some very small entrainment, which however is not significant. To find out what happens with the combined frequency wave stimuli, further work is needed which may include research on even higher frequencies or other kinds of combination waves.

Furthermore, it would be interesting to try and create an entrainment threshold for SSVEP signals. It would, however, require a lot more measurements to create something similar to the perception threshold.

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