Provoking Predetermined Aperiodic Patterns in Human Brainwaves

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In the present work, electroencephalographic recordings of healthy human participants were performed to study the entrainment of brainwaves using a variety of stimulus. First, periodic entrainment of the brainwaves was studied using two different stimuli in the form of periodic auditory and visual signals. The entrainment with the periodic visual stimulation was consistently observed, whereas the auditory entrainment was inconclusive. Hence, a photic (Visual) stimulus, where two frequencies were presented to the subject simultaneously was used to further explore the bifrequency entrainment of human brainwaves. Subsequently, the evolution of brainwaves as a result of an aperiodic stimulation was explored, wherein an entrainment to the predetermined aperiodic pattern was observed. These results suggest that aperiodic entrainment could be used as a tool for guided modification of brainwaves. This could find possible applications in processes such as epilepsy suppression and biofeedback.

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Entrainment is the process of adjusting the rhythms of a system to that of an external system. This is observed in a wide variety of natural as well as laboratory systems [1–6]. In mammals, entrainment of the circadian rhythms as a function of various factors such as illumination, body temperature, social cues and food availability is well studied in literature [3–6]. Another interesting observation in this field is the phenomenon of brainwave entrainment. This phenomenon leads back to the initial experiments done to study the brain dynamics [7, 8], wherein flickering lights at different frequencies were used to study the entrainment in human as well as animal subjects. A recent interest has emerged in the entrainment of brainwaves using a variety of stimulation such as, audio-visual stimulation (AVS) or transcranial alternating current stimulation and its possible applications [11–12]. Research has also been carried out to study the effects of individual auditory [13, 15] and photic [16] entrainment of the brainwaves. Noise along with a subthreshold photic stimulus has previously been shown to enhance the periodicity in brainwaves via stochastic resonance [16, 19]. However, there have been contradicting reports regarding the effects of audio stimulation on the brainwave entrainment [14, 15]. The audio stimulation is conventionally given in the form of binaural beats [11, 12, 17] or repeating drum sounds [15]. Similarly, the photic entrainment is studied using both colored [11, 12] and white light [16] LEDs flickering at a desired frequency. In the present work, entrainment is studied using white light LEDs to avoid the psychological effects of the coloured light [18], if any. Also, the auditory counterpart of white light i.e. white sound was switched on and off periodically to explore the auditory entrainment of brainwaves.

The next step after studying single frequency entrainment would be bifrequency entrainment, wherein two rhythmic photic stimuli are presented to the subject simultaneously. Recently, in synthetic gene oscillators, entrainment was studied using aperiodic signals [20]. Another interesting extension to be explored in this direction would be an aperiodic entrainment of human brainwaves. We have studied the effects of an aperiodic photic stimulation on the electrical activity of the brain. The organization of this paper is as follows. In part I, the protocol employed for the experiments is described. In
part II, results for the periodic photic stimulation are presented. Bifrequency and aperiodic entrainment are reported in part III and IV respectively. A discussion on the results follows in part V.

I. EXPERIMENTAL PROTOCOL

The experiments were performed on five healthy adults (26.12±1.86) who volunteered for the experiments. All participants were informed about the experimental protocol beforehand and the experiments were performed only after the participants signed the Informed Consent Form (ICF). The ICF was approved by the Institute ethics committee of IIT Bombay. A detailed experimental protocol is mentioned in the supplementary material. The protocol for all the experiments was as follows:

0-8 minutes: Relaxed state (Part I)
8-18 minutes: Stimulus applied (Part II)
18-26 minutes: Relaxed state (Part III)
26-36 minutes: Stimulus applied (Part IV)
36-44 minutes: Relaxed state (Part V)

II. PERIODIC PHOTIC STIMULATION

The light signal was provided using a set of 8 white light LEDs mounted on a board. The first set of experiments were performed with all these LEDs synchronously flickering at 10Hz frequency. This value of frequency was chosen to check for the periodic entrainment of the brainwaves with a stimulation in the baseline frequency range (alpha range: 8-13 Hz). Scalp maps were used to ensure maximum entrainment in the occipital head region. The analysis of the results was then performed using the short-time Fourier transform (STFT) to see the evolution of brainwaves in both time as well as frequency domain. The spectrogram function of MATLAB® was used for this purpose. The STFT was calculated using a Gaussian window of 6 s with an overlap of 5.96 s between consecutive windows. The EEG recordings for the Oz electrode were used for the analysis. This was done considering the symmetric location of this electrode between the left and right hemispheres, thus minimizing the effects of right or left handedness of the subject, if any. To quantify the entrainment observed, ζ is calculated and compared across various experimental conditions for Oz electrode. It gives a measure of the increment/decrement in the power of the Oz electrode as the stimulus is turned On or Off and is defined as follows.

\[ ζ = \int_{t_1}^{t_2} \int_{f_1}^{f_2} P(f, t) df dt \]

P represents the power spectral density (PSD) in frequency f at time t. Unless otherwise specified, the values of \( f_1 \) and \( f_2 \) were kept constant at 5 Hz and 40 Hz respectively. This was done to study only the fundamental and super-harmonic entrainment of brainwaves. This range includes all the discernible changes at fundamental and harmonic frequency observed with the entrainment. First two minutes of the cleaned EEG data were used for the analysis across the subjects and for all the experiments. Hence, \( t_1 = 0 \) s and \( t_2 = 2 \) min. To study the effects of the stimulation on the amplitude of the brainwaves, the variance in the amplitude with and without stimulus was compared.

The effect of the 10 Hz photic stimulation on the brainwaves calculated using the techniques mentioned above are presented in Figure 1 and Figure 2. Figure 1 shows the STFT for one of the subjects without (upper panel) and with (lower panel) the stimulus. An increment in the power across the fundamental frequency and the subsequent harmonics can be observed with the stimulus. In Figure 2, increment or decrement in \( ζ \) (left panel) and the amplitude variance (right panel) of the brainwaves with respect to the stimulus being On or Off is presented. A consistent increment in both these quantities is observed when the stimulus is On. Sub-harmonic entrainment of the brainwaves at this
FIG. 1: STFT of the brainwaves (Oz electrode) for the first 2 minutes of without and with 10 Hz photic stimulation. An increment in power at 10 Hz and the subsequent harmonics (20 and 30 Hz) can be observed in the sub-plot with the stimulus.

FIG. 2: Evolution of the quantities $\zeta$ and Amplitude Variance as a function of stimulus status for all the subjects. A universal increment for both these quantities when the stimulus is On is evident from the box plots in both the figures.

frequency was also studied by filtering the data in the frequency range of 4.9-5.1 Hz (sub-harmonic at 5Hz) and studying both $\zeta$ and amplitude variance as a function of stimulus status. A persistent increment in both the quantities when the stimulus is On was observed across all the subjects (results in supplementary material).

Upon observing entrainment using a 10 Hz photic stimulation, the effects of a 6 Hz photic stimulation on the brainwaves were explored. This was done to study brainwave entrainment when the entrainment frequency is relatively farther from the baseline frequency range. As shown in Figures 3, entrainment at fundamental frequency and its subsequent harmonics can be observed when the stimulus is On. However, the entrainment observed at 6 Hz is weaker as compared to the entrainment observed at 10 Hz. This is evident by lesser percentage increment in $\zeta$ and amplitude variance in Figure 4 as compared to Figure 2. Also, the sub-harmonic entrainment for 6 Hz calculated by filtering the brainwaves in the frequency range of 2.9 - 3.1 Hz (sub-harmonic at 3Hz), was not observed across all the subjects (results in supplementary material).

After studying photic entrainment, the next step was to study the effects of auditory stimulation on the brainwaves. For this purpose, an auditory analogue of white light i.e. white sound was used. This sound consists of
the frequencies in the auditory range i.e. 22-22000 Hz distributed uniformly. This sound was then turned **On** and **Off** at the desired frequencies (6 and 10 Hz). However, a consistent increment across all the subjects was not observed using auditory stimulation. Amongst the subjects that did show entrainment, a significantly smaller increment in power was observed as compared to the photic stimulation (a detailed comparison for the same is presented in supplementary material). The results for auditory stimulation in this case are in agreement with those reported in [17] for binaural beat entrainment.

III. BIFREQUENCY ENTRAINMENT

Since a single frequency stimulus was able to entrain the brainwaves, two frequencies were provided simultaneously and the evolution of brainwaves was analysed. For this purpose, half the LEDs were flickering at 6 Hz and the other half at 10 Hz. A simultaneous entrainment to both the frequencies as well as their subsequent harmonics as shown in Figure 5 was observed. Also, an entrainment to the sum of the two different frequencies (6+10 = 16 Hz) was observed. Figure 6 shows the consistency of this pattern across all the subjects for both $\zeta$ and amplitude variance. Bifrequency entrainment was further explored by supplying one frequency to each eye. A persistence of entrainment at the harmonics and summation of the two frequencies was observed. This indicates to the integration of the information received by each eye in the visual pathways of the brain. Since sub-harmonic entrainment was observed using 10 Hz photic stimulation and not with 6 Hz photic stimulation, it was not pursued for the analysis in the subsequent set of experiments. As seen in Figure 5, the bifrequency photic stimulation was able to simultaneously provoke a range of frequencies in the brainwaves. Subsequently, the time required to entrain the brainwaves was investigated. This was done by alternating the entrainment frequency between 6 and 10 Hz. For one time unit, the LEDs were flickering at 6 Hz and at 10 Hz for the next time unit. A shift in entrainment from 6 to 10 Hz upon alternating the flicker frequency from 6 to 10 Hz every second was observed. A further decrement in time was not possible because of the resolution limitations posed by the analysis technique.

IV. APERIODIC ENTRAINMENT

As mentioned in the previous section, entrainment to a single frequency was possible by an exposure to that frequency for one second. Also, the entrainment shifts

![Figure 5: STFT of the brainwaves (Oz electrode) for the first 2 minutes of without and with both 6 and 10 Hz photic stimulation. A discernible increment in power at the fundamental frequencies (6 and 10 Hz) and the subsequent harmonics (12, 18, 20, 24, 30 and 36 Hz) can be observed from the sub-plot with the stimulus. Also entrainment at the sum of the fundamental frequencies (6 + 10 = 16 Hz) is observed.](image)

![Figure 6: Increment/decrement in $\zeta$ and Amplitude Variance when the stimulus was turned On/Off at a simultaneous 6 and 10 Hz photic stimulation. A consistent increment for both these quantities when the stimulus is On can be seen from the box plots in both the figures.](image)
to the next frequency as the stimulus updates to the subsequent frequency. Hence, an aperiodic signal was made with a uniform random distribution of frequencies in the range of 5-15 Hz. The frequency of the signal kept changing randomly from one value to the next every second. This signal was fed to the LEDs and its effects on the brainwaves evaluated. As shown in Figure 7, unlike previous forms of entrainment, no consistent entrainment at a single frequency is observed. This is because the entrainment state is shifting every second due to the change in frequency values every second. In Figure 8, the increment/decrement in $\zeta$ and amplitude variance as the stimulus is turned On/Off persists as a consequence of entrainment. The response provoked in the brainwaves by the light signal was visually inspected. A local increment at the instantaneous stimulation frequency was observed in the brainwaves. As the stimulus changes to the next frequency, the brainwave entrainment was also found to shift towards this next frequency in the sequence. To further check if the brainwaves were following the predetermined aperiodic signal supplied through the LEDs, information transfer between the light signal and the brainwaves was quantified. In the data cleaned for this purpose, the previously rejected epochs of noisy data were replaced with zeros. This was done to maintain a uniform length of the time series. $P_k(f_i, t_i)$ represents the PSD in the frequency range of $f_i$ to $f_i + 1$ Hz and a time window of $t_i$ to $t_i + 1$ s. The time windows in this case are non-overlapping. The subscript $k$ indicates to the five parts of the experiment as mentioned in the protocol. To reiterate, during part 2 and 4, the photic stimulation was provided and part 1, 3 and 5 are without stimulation. $P_k(f_i, t_i)$ denotes the PSD for the light signal. PSD from part 1, 3 and 5 was used for defining a threshold ($th$) which is employed as an indicator of power in a frequency band without the stimulus. The PSD was then modified as follows:

$$P_k(f_i, t_i) = \begin{cases} P_k(f_i, t_i) & \forall \quad P_k(f_i, t_i) > th \\ 0 & \forall \quad P_k(f_i, t_i) < th \end{cases}$$

$C_k$ is a measure of correlation between the STFT of the brainwaves and the light signal. It is defined as follows:

$$C_k = \frac{\sum_{i=5}^{15} \sum_{t_i=0}^{400} P_k(f_i, t_i)P_s(f_i, t_i)}{N_k}$$

$P_s(f_i, t_i)$ and $P_k(f_i, t_i)$ have been defined previously. First 400 s of the data was used for calculating the information transfer in the fundamental frequency range (5-15 Hz). For this analysis, $f_i$ and $t_i$ increase in steps of 1 Hz and 1 s respectively. The normalizing constant $N_k$ denotes the number of non-zero data points in the brain data for the corresponding part of the experiment.

In Figure 9, an increment/decrement in $C_k$ as a function of stimulus status On/Off can be observed. $C_k$ was also calculated for five other surrogate aperiodic signals with the same frequency distribution but different sequence of frequencies. The value of $C_k$ for the original signal was consistently higher as compared to the surrogate signal. A comparison between the $C_k$ values for the original signal and the surrogate signal for one of the subjects is presented in the supplementary material.

V. DISCUSSION

In the results presented above, entrainment is found to persist with different types of stimulus including periodic, bifrequency and aperiodic photic stimulation. The STFT plots across various forms of stimulus show entrainment for one subject while the box plots represent the robustness of the phenomenon against subject variability. The decrement in $\zeta$ and amplitude variance after the stimulus is removed is a manifestation of the underlying information processing area. The effect of stimulation dies down after the system stops receiving the
external information. The increment in amplitude variance of the EEG signal when the stimulus is On is an indicator of increased neuronal firing in the corresponding region of the brain. This can be loosely compared to a stimulus provoked increased blood flow in a specific brain region observed using various neuroimaging techniques. In bifrequency entrainment, a simultaneous increment in power at the fundamental, harmonic and summation of frequencies was observed. Aperiodic entrainment, in our opinion, is of special interest as it might have a wide applicability. One possible application could be in the field of biofeedback. The brainwaves of a healthy individual during various stages could be recorded and fed back to them as a visual stimulus. In certain pathological conditions such as some forms of epilepsy (petit mal epilepsy), low frequency rhythmic activity in the brainwaves is observed. An aperiodic pattern lying outside this rhythmic activity and centred near the baseline state of the subject might lead to the modification of the brainwaves to the desired state. An aperiodic entrainment of circadian rhythms may also be looked into.

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