Neurophysiological evidence of the cognitive cycle and the emergence of awareness

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Abstract—As part of the developing body of research about neural correlates of higher cognitive functions and awareness we have recently reported that the creation of knowledge and meaning could be manifested via Cortical Singularities. In this work we present new neurophysiological evidence of the hypothesized cognitive cycle in the emergence of awareness when a presumable meaningful stimuli is presented to an animal. This stimulus is manifested in the neocortex, as the creation of the knowledge necessary for intentional behavior and decision making. The results are interpreted through the concept of Pragmatic Information, which is complementary to the Shannon Entropy Index. We identify large-scale synchronization across broad frequency band as potential manifestation of the ‘aha’ effect, indicating the construction of knowledge and meaning from input sensory data and leading to awareness experience.

Keywords - Electro-corticogram, Hilbert Transform, Synchronization; Analytic Amplitude; Analytic Phase; Criticality; Awareness; Cognition, Pragmatic Information, Cognitive Cycle, Intentionality, Knowledge and Meaning.

I. INTRODUCTION

As a complementary study to understanding of neurophysiological processes manifesting higher cognition and consciousness using fMRI, PET, MEG, and other advanced techniques [1-5], we have focused on the analysis of ECoG signals over a 64-channel array on the visual cortex in rabbits. We have defined some indexes based on the concept of pragmatic information [7, 8], inspired by the work of Freeman and others related to spatio-temporal analysis on brain dynamics [9, 10]. The goal is to identify moments of synchronization of neural activity across large cortical areas related to higher cognition and the benefits associated with analyzing ECoG and EEG signals; for a comprehensive review see Freeman and Quirroga [6].

Brains can be viewed as open thermodynamic systems operating near the state of criticality. Intermittently they exhibit synchronization and de-synchronization transitions [11-13]. To create meaning, the brain needs to produce knowledge from sensory data by associating meaning to events. This knowledge can be monitored through spatio-temporal ECoG patterns.

In order to capture this dynamics at the level of neuronal populations, we need some form of measurement based on energy consumption, work, force, and electro-magnetic fields that we could associate to actions in the world. Meaning, knowledge and intentions can be derived from actions, and according to the field of semiotics, the concept of pragmatic information has been defined as a complementary concept to the Shannon information entropy index [14]. Pragmatic information (PI) is used in physics to characterize multimodal instabilities. We propose that application of PI to the analysis of brain signals would allows us to derive meaning and knowledge from EEG or ECoG data [14, 15]. Our hypothesis is that a set of PI indices would allow us to capture the goal-oriented action aspect of the cognitive cycle.

The present work is the continuation of studies with rabbit electrocorticogram (ECoG) data, particularly the work of John Barrie and Mark Lenhart in the Freeman Lab at Berkeley [21], as well as some more recent studies [16, 17, 23]. Previous studies showed that synchronization effects observed in ECoG arrays have significant invariance over a broad-range of frequencies, including gamma-, beta-, alpha-, and theta bands.

We review our first intuitive findings and then we present new evidence based on the analysis of a series of experiments over the visual cortex of one rabbit [23, 25]. Our ultimate goal is to conduct a robust analysis based on multiple runs and several rabbits to obtain statistically significant discrimination among various stages of the cognitive process. In this paper, however, we present initial evidence pertaining the presence of a cognitive cycle comprised of five distinct stages or steps in a window of one second past the visual stimuli for one rabbit.

To this end we create and study movie sequences created for each of the 39 runs over the rabbit visual cortex, including Analytic Amplitudes, Instantaneous Frequencies and other measurements. In the experiments, we used signals from an 8x8 spatio-temporal array of electrodes implanted over the cortex of the rabbit. We performed band-pass filtering and
Hilbert transform over the data, for the frequency bands of interest, namely: theta, alpha, beta, and gamma.

We used the pragmatic information indexes described in previous studies [16,17, 23]. These indices implicitly take into consideration the amount of work that is required to create knowledge expressed in meaningful actions. Several of the indices can be interpreted as equivalent forces driving meaningful action based on the knowledge previously created. Next we describe clear synchronization effects during intensive cognitive activity, indicating the detection and potential classification of previously learnt conditioned stimuli. Finally, we point to some limitations of our analysis and how to overcome such limitations in future research. Our work has the potential to shed light on constructive aspects of intention, creativity, in the context of universal values and behavioral responses, for the future benefit and the peaceful development of humanity [18, 19].

II. DESCRIPTION OF ECOG EXPERIMENTS AND DATA PREPROCESSING

Experimental data obtained from intracranial arrays of 8x8 electrodes implanted over the visual cortex of rabbits at the Freeman Neurophysiology Lab at UC Berkeley [20-23]. The animals were trained under the classical conditioning paradigm. As a result, they have learned discrimination when one stimulus was reinforced (CS+) and the other was not (CS−). Once the animals have been trained, experiments have been conducted with CS+ and CS- stimuli. A single experiment contained 6 s, in which the first half (3 s) has been used to establish the background reference state. At time 3 s, a stimulus (light flash) has been presented to the animal and the response has been recorded for 3 s. The first and last 0.5 s are omitted as those periods are used for the proper widowing functions.

We follow the preprocessing steps as described in previous studies [16,17]. Accordingly, first we analyze the 64-channel ECoG signals, perform preprocessing and band-pass filtering over each channel. Next we determine the analytic signals after Hilbert transforming the band-passed ECoG data. The analytic amplitude of each channel is denoted as $A_j(t)$, $i = 1, \ldots, 64$. We use notation $P_j(t)$ for the analytic phase, $P_j(t)$, $i = 1, \ldots, 64$.

<table>
<thead>
<tr>
<th>Frequency Band</th>
<th>$F_{stop}$ Hz</th>
<th>$F_{passL}$ Hz</th>
<th>$F_{passH}$ Hz</th>
<th>$F_{stopH}$ Hz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theta</td>
<td>3</td>
<td>4</td>
<td>6</td>
<td>7</td>
</tr>
<tr>
<td>Alpha</td>
<td>8</td>
<td>9</td>
<td>11</td>
<td>12</td>
</tr>
<tr>
<td>Beta</td>
<td>12.5</td>
<td>16.5</td>
<td>21</td>
<td>24</td>
</tr>
<tr>
<td>Gamma</td>
<td>24</td>
<td>30</td>
<td>36</td>
<td>40</td>
</tr>
</tbody>
</table>

Band-pass filters are applied in the theta, alpha, beta and gamma bands with the following parameters given in Table I. The applied Hilbert transform methodology and the analytic signal construction followed the approach already described in previous studies [15-17, 23]. The comprehensive analysis of all 64 channels in the 39 experiments, over various frequency bands produced a large amount of data, which could not be presented fully in this report. Here we illustrate the behavior of the ECoG signals and the analytic signals over the gamma band for one experiment (run #2).

Figures 1 and 2 show the filtered ECoG signals in all 64 channels for this trial on the theta and gamma bands. These figure shows four sub-graphs which are: signal amplitudes (SA) of the 64 channels (top), the 64 channel’s analytic amplitude (AA) (middle top), the Log analytic phase of the signals (middle bottom), and the absolute analytic frequency all derived from the instantaneous phase differences (bottom) after Hilbert transform.

Figures 1 & 2 show that, most of the time, the ECoG channels are highly synchronized and have relatively small amplitudes with the exception of the post-stimulus period (3–4 s). There is significant variation over the post-stimulus period in the ECoG signals (SA), but the most prominent changes are seen in the analytic amplitudes (AA). The analytic phase value (AP) exhibit intermittent variations as time evolves, which is exemplified by the instantaneous frequencies (IF) in the form of large diverse spikes.

![Figures 1 & 2](image-url)

Figure 1. Illustration of the analyzed rabbit ECoG data in experiments #2 filtered over the Theta band. Each of the subplots show 64 curves corresponding to the ECoG signals, analytic signals, unwrapped phases, and instantaneous frequencies, from top to bottom, respectively. The Theta band signals where filtered over a pass band from 4 Hz to 6 Hz.

The above observations also apply to the theta, alpha, beta and the gamma bands. However, the gamma band exhibits much more intensive variations of the instantaneous frequencies, and there seem to be two regions in the post-
stimuli period with large SA and AA values, separated by intermittent drop in SA and AA. The intermittent drop is seen in beta, but absent in theta and alpha bands.

Figure 2. Illustration of the analyzed rabbit ECoG data in experiments #2 filtered over the Gamma band. Each of the subplots show 64 curves corresponding to the ECoG signals, analytic signals, unwrapped phases, and instantaneous frequencies, from top to bottom, respectively. The Gamma band signals where filtered over a pass band from 30 Hz to 36 Hz.

It is difficult to make more quantitative conclusions based on these displays for AA, SA, AP, and IF. To discriminate better the effects of the stimuli after training the animal, we produced a set of 39 movies for each band, for the values (over the 64) channels of the AA, SA, AP, and IF. This allows us to observe the evolution of the spatial patterns over time. In a following section, we introduce snapshots from the movies to study through the art of encephalography, Informed Visual Inspection, the spatio-temporal patterns associated with the hypothesized cycle of knowledge and its different stages. We present the results of condensing the observed cycle of knowledge with the aid of the Pragmatic Information indices for the Alpha, Beta and Gamma bands.

In is important to emphasize the potential role of the spatially distributed AA and SA patterns concerning the meaning that the animal associates with the stimuli and its usefulness in decision making [1, 10, 15, 21, 22, 26]. Eventually, we aim at deriving classification methods based on the distributed SA and AA patterns. However, this goal is outside the scope of this paper.

In the next section we systematically review our intuitive findings as explained in a previous paper [23]. In that study we introduced various statistical measures over different bands in order to analyze the fine structure of the post-stimulus response period. We showed detailed results obtained for various bands and this helped to illustrate major features of the Hilbert analysis and its usefulness in deriving the pragmatic information indexes.

III. REVIEW OF OUR FIRST INTUITIVE FINDINGS

Synchronization-de-synchronization effects with sudden transitions in spatio-temporal neurodynamics have been found in ECoG data [23]. Here we study the potential relevance of those findings to cognition and awareness.

Our analysis highlighted the period between 3-4s, which seemed to be divided into the moments between 3-3.5s and the one between 3.5-4s showing distinct behaviors. Particularly we showed that in the period between 3.25-3.5 seconds the frequency dispersion dropped dramatically around the mean due to a very high synchronization moment. This then was followed by a dramatic increase in dispersion (desynchronization) between the period 3.5-4 seconds for both the SA and AA and we suggested that perhaps the AA measures could provide a more powerful discrimination. As this analysis was done based on visual inspection of few runs we warned that in the future, detailed hypothesis tests would be required to validate the introduced measures as useful correlates of classification performance based on the observed ECoG amplitude and phase patterns.

Our intuitive conclusion and following conjecture indicated that the moments of very high synchronization after stimuli (3.25-3.5 seconds) may reflect moments of intense attention followed by a learning and integration period with very high de-synchronization (3.5-4 seconds) as shown in Figure 2. Similar results were obtained over different bands. These observations also clearly pointed to the onset of significant synchronization during 3.2-3.5s, which was suddenly terminated during 3.5-4s, however, the AA magnitude remained very high until about the 4th second, and suddenly dropped afterwards.

Though this has been a very first, preliminary analysis, we observed that the Pragmatic Information indices captured the changes numerically. Consequently, we suggested employing these observations to derive means to classify events and neural correlates using some form of mathematical algorithm, based on discriminant analysis. The observed effects indicating the synchronization-de-synchronization transition during the 1s post stimulus period were much more prominent in the gamma and beta narrow bands (taken in increments of 2 Hz). Though less prominently, these effects were also observable in the theta and alpha bands. This meant that we documented an important intra-cortical effect across frequencies 4Hz to 40 Hz.

One of the important findings was that our analysis shed some new information regarding previous studies where it was shown that AM patterns could have discriminative power during the first 200 ms after the stimulus (Type I effect), and towards the end of the 1000ms post stimulus period (Type II effect) [23, 24]. Looking at the results of our work, we also see the prominence of the 1s post stimulus period coinciding with the above mentioned studies, however, the regions of interest seemed more complex in our analysis and complementary to the already documented results.
solve the task, which is marked by lar
takes about 0.2-0.3s. Finally, after 0.8-1
a new AM pattern. The consolidation of the
synchronization for a period of about 0.3s.

Figure 2. Analytic Amplitude (AA) of the signals after Hilbert transformation; the signals have been filtered over various temporal frequency bands at constant 2Hz bandwidth segments; each plot displays the analytic amplitude (AA), standard deviation of the AA, and the average frequency over the given narrow 2Hz frequency band in logarithmic coordinates; (a) beta (12Hz-26Hz); (b) low gamma (26Hz-40Hz).

Specifically, we saw a strong synchronization during the 3.25-3.5s period, which switches to de-synchronization during the 3.5-3.75s period. Interestingly, precisely this is the period when the AM classification does not work according to [23-24]. We suggested that during this intermit

de-synchronization period the spatio-temporal dynamics rapidly changes, which may be a reason of the absence of classifiable AM patterns.

We derived new insights on the spatio-temporal neurodynamics concerning decision making, during which the subject tries to solve the classification task. A possible interpretation was given as follows: after a brief de-synchronization period of approx. 0.2s, the subject tries to solve the task, which is marked by large-scale cortical synchronization for a period of about 0.3s. At the end of this 0.3s period, a possible solution starts to emerge in the form of a new AM pattern. The consolidation of the new AM pattern takes about 0.2-0.3s. Finally, after 0.8-1s following the

stimulus, the new AM pattern leads to successful classification. After the successful classification, the subject is satisfied and loses interest in the stimulus and returns to the background activity.

Clearly, extensive future studies are needed to better understand the observed dynamics and to validate or reject the preliminary hypothesis outlined in [23-24]. In the following sections we introduce new evidence of the cognitive cycle and the emergence of awareness experience in the neocortex based on the observation of spatio-temporal patterns of SA, AA, AP and IF projected as a movie displaying the 39 runs simultaneously. We complement this intuitive learning process with the Pragmatic Information Indices derived from information theory and semiotics as described in previous studies [16,17 and 23].

IV. NEW EVIDENCE OF THE COGNITIVE CYCLE BASED ON INFORMATION THEORETIC INDICES FOR 39 RUNS

Here we introduce the condensed results of 39 runs based on rabbit ECoG experiments on the visual cortex. We briefly introduce the reader to a set of pictures or snapshots taken from the 3D movies displaying only 30 of the 39 runs of the Log AA(t)^2 for the Gamma band. Each picture (1-5) is associated with one of the steps of the hypothesized knowledge cycle, respectively:

- Step 1 (3 - 3.1 s): Initial impression, which may be termed the “Awe” moment.
- Step 2 (3.1 – 3.3 s): Chaotic Exploration of memory traces with highly distributed and desynchronized patterns.
- Step 3 (3.3-3.45 s): Recognition/identification of the searched clue/decision and it can be termed the “Aha” moment.
- Step 4 (3.45 – 3.6 s): Integration of the new knowledge in a chaotic dynamic process.
- Step 5 (3.6 – 3.9 s): Dramatic drop in the indices toward the end of the post-stimulus brain activity, showing a return to the usual, background level.

The following pictures describe the systems dynamics for the knowledge cycle. The behaviors for the AA(t)^2 are very different for each Step but very similar across the 39 runs within each Step.

Step 1 shown in Figure 3; it is characterized by a moment of high synchronization and low amplitudes for all runs. In Fig. 4, Step two, we observe a de-synchronization period where initially the AA(t)^2 drops dramatically in some regions of the 8x8 spatial array. These drops are known also as “null spikes” in the previous studies presented in [6, 13]. These are followed by a strong increase of the AA in large regions of the spatial array, usually different than the region where the “null spikes” take place. We see a combination of situations in each movie where some are showing drops, others the “null spike” and others the high amplitudes.
In Figure 5 we can observe the behavior associated with the “Aha” moments where we observe a tendency towards synchronization and drops of AA amplitudes reflected in the Log AA(t)^2. The 39 run tend to drop together in this period of time showing us a consistent behavior in a form of metastability. Step 4 is the Chaotic Integration period as shown in Fig. 6. Figure 6 shows a similar behavior as the step of Chaotic Exploration in Fig. 4 with strong and more abundant “null spikes” as well as a higher rise in AA. Figure 7 simply shows the tendency of the system to return to background state. At background state, most of the time we observe the system is in a synchronized state displaying low amplitudes, with periods of mild de-synchronization and relatively high amplitudes.

Following, we complement this interesting and robust study of the system through movie watching and careful observation with the results obtained with the aid of a systematic statistical analysis of the data with the calculation of the different Pragmatic Information indices.
peaks were found for T = 0.0625s as well, not shown here. This shorter window size is considered optimum for the gamma band by Freeman which almost coincide with T = 0.06 s minimum window size according to Freeman’s method [11, 12]. When contrasted with window size T = 0.125 s, we observe decreased resolution, i.e., the peaks merge into 2 peaks for the majority of indexes and to three peaks for one of them.

The size of the peaks tends to behave slightly differently for the indexes calculated according to Freeman’s method and using the rest of the indexes. Overall the observed indexes and our previous analysis revealed the synchronization between bands of de-synchronization within bands post stimuli for the period 3-4 s.

V. DISCUSSIONS

Based on the newly introduced experimental findings, we can make some important conclusions. Clearly, the period between 3-4 s is significantly different from the rest of the time segments for all frequency bands. In that period, the moments between 3-3.5 s and between 3.5-4 s are also significantly different.

Our present detailed analysis reveals a refined structure of the peaks in the post-stimulus interval. This poses the possibility to formulate a new hypothesis where a more accurate understanding of the cycle of knowledge creation may be achieved. The results are summarized in Table II.

Table II. Overview of the Knowledge Creation Cycle

<table>
<thead>
<tr>
<th>Knowledge Creation Cycle Steps</th>
<th>Awe</th>
<th>Chaotic Exploration</th>
<th>Aha</th>
<th>Chaotic Integration</th>
<th>Background Activity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle Steps Order</td>
<td>Step 1</td>
<td>Step 2</td>
<td>Step 3</td>
<td>Step 4</td>
<td>Step 5</td>
</tr>
<tr>
<td>Post Stimulus Period</td>
<td>3 - 3.1 s</td>
<td>3.1 - 3.3 s</td>
<td>3.3 - 3.45 s</td>
<td>3.45 - 3.6 s</td>
<td>3.6 - 3.9 s</td>
</tr>
<tr>
<td>Characteristic Behaviour</td>
<td>Hyper synchronisation and low AA²</td>
<td>Desynchronisation with dramatic drops (&quot;null spikes&quot;) followed by a strong raise for AA²</td>
<td>Tendency towards synchronisation and drops of AA²</td>
<td>Strong desynchronisation with abundant &quot;null spikes&quot; and a strong raise in AA²</td>
<td>Synchronisation with low AA² &amp; occasional desynchronisation periods showing high AA²</td>
</tr>
<tr>
<td>Similarities</td>
<td>Similar behaviour to &quot;Aha&quot; (Step 3)</td>
<td>Similar behaviour to &quot;Chaotic Integration&quot; (Step 4)</td>
<td>Similar behaviour to &quot;Aha&quot; (Step 1)</td>
<td>Similar behaviour to &quot;Chaotic Exploration&quot; (Step 2)</td>
<td>Usual Background Activity</td>
</tr>
</tbody>
</table>

It is likely that each band tells us a different story about the cycle of knowledge creation in the cortex, which is necessary for intentional behavior. Different bands give us different clues for what to look when searching for cognitively relevant features. For example, theta band shows the beginning and end of the cognitive/learning cycle, so acting as a gating band. Alpha gives us the different significant nonlinear events within the cycle. In addition we hypothesize that beta could be showing us that other complexities, perhaps the consumption of energy or the amount of work done in each stage in order to create knowledge differs from stage to stage. This could mean that the first part of the cycle is more energy consuming (big peak) than the 2nd half of the cycle (small peak). The gamma
band may pose even more refined level of complexities, which remains difficult to assess at the present time.

VI. CONCLUSIONS AND FUTURE PERSPECTIVES

In this work we describe a methodology for brain signal analysis by introducing a set of indices to detect the onset of synchronization of neural activity across large cortical areas during high-level cognitive functions and awareness experience [25]. Our indexes of Pragmatic Information can serve as a solid starting point to quantitatively approach the relationship of brain and mind. The construction of meaning is likely associated with the cognitive cycle involving the subject embedded in and interacting with its environment, rather than in the disembodied input signals. Cinematic theory of cognition is extremely valuable to describe the nature of meaning in brain dynamics.

We analyzed rabbit ECoG data and identified synchronization effects with sudden transitions in spatio-temporal neurodynamics in the brain of the rabbit. The analyzed response period shows various significant nonlinear events within the cognitive cycle in the 1 s window following stimuli.

- We propose an interpretation of the findings as follows. Starting with “Awe” (3-3.1 s), chaotic exploration (3.1-3.3 s) follows, leading to the “Aha” (3.3-3.45 s) moment. Next, chaotic integration (3.45-3.6 s) takes place, and finally a dramatic drop (0.6-0.9 s) indicates a return to the basal brain dynamics.
- The present analysis provides important details on cognitive processing exactly during the critical transition period of chaotic exploration, when the subject solves the classification task. We hypothesize that this effect is associated with awareness experience. This hypothesis is in line with Freemans's earlier intuition regarding the construction of knowledge and meaning in brains.
- In the future, the estimation of confidence intervals around the times where the steps of the knowledge cycle take place can provide further clarification on the underlying processes.
- Future studies are planned by measuring EEG activity in humans while in states of relaxation, peaceful existence, and physiological coherence mediated by breathing, and compare with mental activity while engaged in unpleasant energy depletion activities leading eventually to stress.

Our approach aims at finding structures for meaning and knowledge in brain dynamics through intermittent synchronization [26, 27] together with states of being such as peace, compassion, love and humor. These ideas can help to establish a long-term research framework to study and understand creativity, scientific insight and spiritual experience through EEG.

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