Procedia Computer Science
Volume 53, 2015, Pages 56–63
2015 INNS Conference on Big Data

The Art of Encephalography to Understand and Discriminate Higher Cognitive Functions Visualizing Big Data on Brain Imaging using Brain Dynamics Movies

Jeffery Jonathan Joshua Davis[1], Robert Kozma[2] and Walter J. Freeman[3]
[1] *The Embassy of Peace, Whitianga, New Zealand*
[2] *Center for Large-Scale Integrated Optimization Networks, Department of Mathematical Sciences University of Memphis, Memphis, TN 38152, USA*
[3] *Division of Neurobiology, Department of Molecular and Cell Biology, University of California at Berkeley, Berkeley, CA 94720, USA*
joshua_888@yahoo.com, rkozma@memphis.edu, dfreeman@berkeley.edu

Abstract
In recent decades a significant effort has been directed towards experimental and theoretical approaches aiming at the establishment of neural correlates of higher cognitive functions and awareness. These efforts produce massive amounts of data on imaging brain structure and functions, and efficient methods are in high demand to make these data easily accessible and understandable to human experts. Here we describe the development of qualitative tools and methodologies where large quantities of brain imaging data are processed and displayed for the purpose of visually discriminating the various stages of the cognitive processes. In this work we report and describe in detail a methodology inspired by the art of encephalography, whereby brain dynamics movies are created based on experimental data. The results are presented to identify large-scale synchronizations and de-synchronizations across broad frequency bands as a potential manifestation of the cycle of creation of knowledge and meaning. This visual process is also useful for the description of learning and adaptation processes in brains.

Keywords: Big Data, Brain Imaging, Electrocorticogram, Visualization, Synchronization, Cognitive Cycle.

1 Introduction

We invite the reader to have a look at the numerous fascinating successes that have been reported in the past decade concerning the neurophysiology of higher cognition and consciousness, producing massive amounts of brain imaging data obtained by functional magnetic resonance imaging (fMRI),

Selection and peer-review under responsibility of the Scientific Programme Committee of INNS-BigData2015

doi:10.1016/j.procs.2015.07.279

magnetoencephalograms (MEG), electrocorticograms (ECoG), and electroencephalograms (EEG) (Freeman W. J., 1999), (Del Cul, Baillet, & Dehaene, 2007), (He & Raichle, 2009), (Koch & Tononi, 2011). In the present work we focus on measuring evoked potentials over the cortex through ECoG and over the scalp by EEG, when we consider the benefit of providing direct and prompt information on the electrochemical processes underlying brain operation (Freeman W. Q., 2012). Based on such measurements, the development of information-theoretical indices to characterize behavior (Hild, Erdogmus, Torkkola, & Principe, 2006) with special emphasis in detecting the onset of synchronization of neural activity across large cortical areas related to higher cognition has been very useful in providing an initial understanding of the dynamics which are produced by the brain when processing a stimuli in order to create knowledge and meaning.

One of the major challenges has been to devise means to discriminate between cognitive states and sensory stimuli based on brain imaging data. It is an important goal to develop quantitative methods for performing such classifications automatically, without the need of human experts. However, there is a need to provide a tool to support human experts such as physicians to perform the classification and diagnostics with the human eye by watching brain dynamics movies. This approach we call the art of encephalography (Borges I, Filomena V, Faoro M, & Perez de Pernia, 1985). This work presents a new methodology based on the art of encephalography, in order to create brain dynamics movies to allow the visualization of different indices simultaneously, as well as the identification of synchronization and de-synchronization transitions (Borges I, Filomena V, Faoro M, & Perez de Pernia, 1985), (Kozma, Puljic, & Freeman, 2012), while presumably the brain is creating knowledge and meaning. This methodology highlights the importance of visual inspection and training on ECoG and EEG signals.

The idea was to produce a set of different three-dimensional perspective displays (3D) as well as a set of plane perspective displays (2D), a vista from above, where large quantities of data are presented simultaneously for visual inspection and study. For this purpose we created three (3) different types of displays, which provide different information and complement each other. These displays allow a visual impression of the following: (1) significant brain events for each measurement, (2) significant brain events across bands and (3) the different stages of the cycle of creation of knowledge and meaning (Davis & Kozma, 2012), (Davis & Kozma, 2013). The final product is a set of 32 movies that provide insight into different aspects of cognition and learning, and particularly about the hypothesized cycle of creation of knowledge and meaning (Davis, Kozma, & Freeman, 2013) in the window of 1 s post visual stimuli.

In this paper, we start with a brief characterization of the rabbit ECoG experiments, followed by an introduction of the Hilbert transform-based signal processing approach. We define the measurement indices used and explain in detail the process of production for the different movie displays. Some movie-frames of the different displays are presented to show the benefits of this methodology and how these brain dynamics movies can aid in discriminating the various stages of the cognitive process. The aim is to produce a wide bank of movies, of different data and different indices, which would be uploaded to a website with the purpose of sharing and opening the door for an interdisciplinary study about the creation of knowledge and meaning. Next we describe the visual findings, which point to the clear synchronization and de-synchronization. Finally, we also point to some limitations of our methodology and how to overcome such limitations in the future. Our work has the potential to shed light on the constructive aspects of intention and creativity, in the context of universal values and behavioral responses, for the future benefit and peaceful development of humanity (Davis J. J., 2009).

2 Brain Dynamics Movies Production Methodology

In order to test the proposed movie making methodology we used experimental data obtained from intracranial arrays of 8x8 electrodes implanted over the visual cortex of rabbits at the Freeman Neurophysiology Laboratory at UC, Berkeley (Barrie, Freeman, & Lenhart, 1996), (Freeman W. J., 2000). The animals learnt to discriminate a stimulus under the classical conditioning paradigm, where one stimulus was reinforced (CS+) and the other was neutral (CS−). Once the animals were trained, experiments were conducted to test the discriminative power and the learnt behavior of the rabbit when presented with CS+ and CS- stimuli. Each experiment was 6 s long. The first half (3 s) was used as the background reference state. At time 3 s, a stimulus (light flash) was presented to the animal and the response was recorded for the last 3 s. The first and last 0.5 s were omitted since those periods were affected by the filtering procedure and particularly by the order of the Finite Impulse Response (FIR) filter applied. We follow the preprocessing steps as described in previous studies (Kozma, Davis, & Freeman, 2012). The index measurements that we used for the creation of the MATLAB movies were: the signal amplitude (SA), the analytic amplitude (AA) and the instantaneous frequency (IF). Band-pass filters were applied in the theta (4-6 Hz), alpha (9-11 Hz), beta (16.5-21 Hz) and gamma (30-36 Hz) band. The applied Hilbert transform methodology and the analytic signal construction followed the approach described in (Kozma, Davis, & Freeman, 2012).

Figure 1 shows the steps followed in the creation of the different displays of movies of different measures or indices for the rabbit ECoG signals. Following is a description of the steps to produce the three (3) different types of brain dynamics movies:

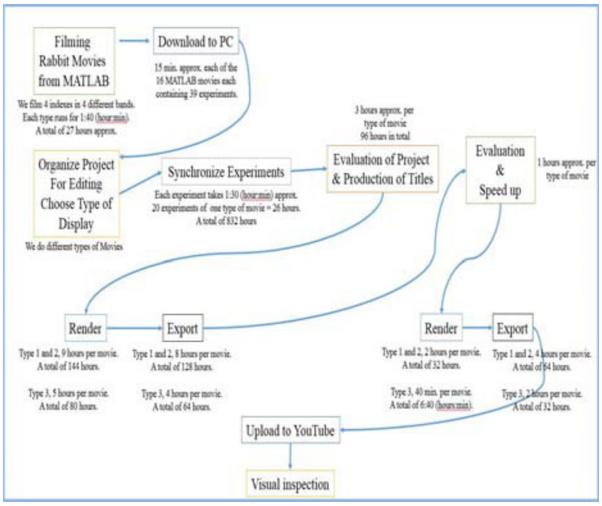

Figure 1: Movies Making Procedure Diagram

Step 1. Prepare the MATLAB code in terms of band filter parameters, type of index and type of display (2D or 3D perspective). The four indices used are: signal amplitude minus average in 2D (SA2D), signal amplitude minus average in 3D (SA3D), absolute values of instantaneous frequency in 3D (abs (IF)) and Log10 of the analytic amplitude squared (Log10 AA2). Record the MATLAB movies for 39 experiments and for the four different indices in the four different bands (624 movies in total). It is important to note that each movie for each experiment for one (1) index for a particular band is recorded in MATLAB time with a pause slow enough (0.1 s) to capture every frame or spatial pattern for each time step.

Step 2. *Download to the computer the 16 MATLAB movies,* each containing the 39 experiments for a duration of approx. 15 min each movie for a total of approx. 240 min or 4 hours. (~15 min/movie x 16 movies ~ 240 min ~ 4 hours).

Step 3. *Organize the editing project (1 per movie) in an editing software program according to the type of display to be produced (approx. 25 minutes per project). T*he 3 types of movies produced:

- **Type 1** exhibiting the 4 different bands (Theta, Alpha, Beta and Gamma) per index with a total of 8 movies;
- **Type 2** exhibiting the 4 different indices (SA2D, SA3D, Log_{10} AA^2, IF) per band with a total of 8 movies;
- **Type 3** exhibiting the 39 experiments per index per band with a total of 16 movies;

Step 4. *Synchronize experiments included in the editing project.* It is important to note that each experiment takes around 1.5 hours to synchronize. Each movie is comprised of 20 experiments, both for displays **Type 1** and **Type 2,** resulting in a total of 30 hours of intensive work needed to accomplish the synchronization task of one movie. There are eight (8) **Type 1**, eight (8) **Type 2** and sixteen (16) **Type 3** movies. Therefore, for all 32 movies the total time associated with the synchronization task amounts to approx. 960 hours . (~30 hours/movie x 32 movies). As it can be noticed, this step is the most strenuous and time consuming for the analyst.

Step 5. *Corrections, and art editing.* This step takes around 3 hours per movie, which makes a total of (~3 hours/movie x 32 movies) approx. 96 hours.

Step 6. *Rendering an editing project.* This step takes approx. nine (9) hours in a i7-4700MQ CPU for each project concerning **Type 1** and **Type 2** displays for a total of around (~9 hours/editing project x 16 editing projects) ~144 hours. The rendering time required gives a total of ~224 rendering hours.

Step 7. *Exporting edited movie.* This step takes approx. eight (8) hours for a high definition movie (1920:1080ppx) in a i7-4700MQ CPU for each **Type 1** and **Type 2** movies for a total of (~8 hours/movie x 16 movies) ~128 exporting hours.

Step 8. *Finalizing corrections and speed calibration.* If everything is in order, in other words there is no need for further corrections, the movie is imported into the project and is doubled in speed to produce the final movie. This process takes around eight (8) hours.

Step 9. *Final rendering.* This task takes approx. 2 hours per movie for **Types 1** and **Type 2** and approx. 40 minutes per movie for **Type 3**, for a total of (~2 hours/movie x 16 movies + 0.6667 hours/movie x 16 movies) ~ 42 final rendering hours.

Step10. *Exporting Final Movie.* This task takes approx. 4 hours per movie for **Types 1** and **Type 2** and approx. 2 hours per movie for **Type 3**, for a total of (~4 hours/movie x 16 movies + 2 hours/movie x 16 movies) ~ 96 final exporting hours. The finished movies are uploaded to a web page on YouTube (Freeman W. J., 2015), (Davis J. J., 2015), for detailed study and sharing with the larger community across continents.

3. Main Observations

In this section we present movie-frame illustrations of the movies we have produced, with the aim of showing the benefits of displaying brain EEG and ECoG signals in the way we have suggested. We start with a set of movie-frame illustrations, which identify the brain events associated with the different stages of the hypothesized cycle of creation of knowledge and meaning; for details see (Davis & Kozma, 2013), (Davis, Kozma, & Freeman, 2013), (Davis, Ilin, Kozma, & Myers, 2014). Following, we briefly introduce the reader to these five (5) steps:

1. ***Awe moment:*** the initial distinct and strong impression that is due to direct exposure to novel and unexpected sensory stimuli.
2. ***Chaotic Exploration:*** the exploration of memory traces that describe the brain as a dynamical system searching through its reservoir of past experiences.
3. ***Aha moment***: the recognition/identification of the searched clue for making a decision.

4. ***Chaotic Integration:*** a step whereby new knowledge is integrated as chaotic attractors in a dynamical system.
5. ***Background Activity:*** return to the basal brain dynamics indicated by a dramatic drop.

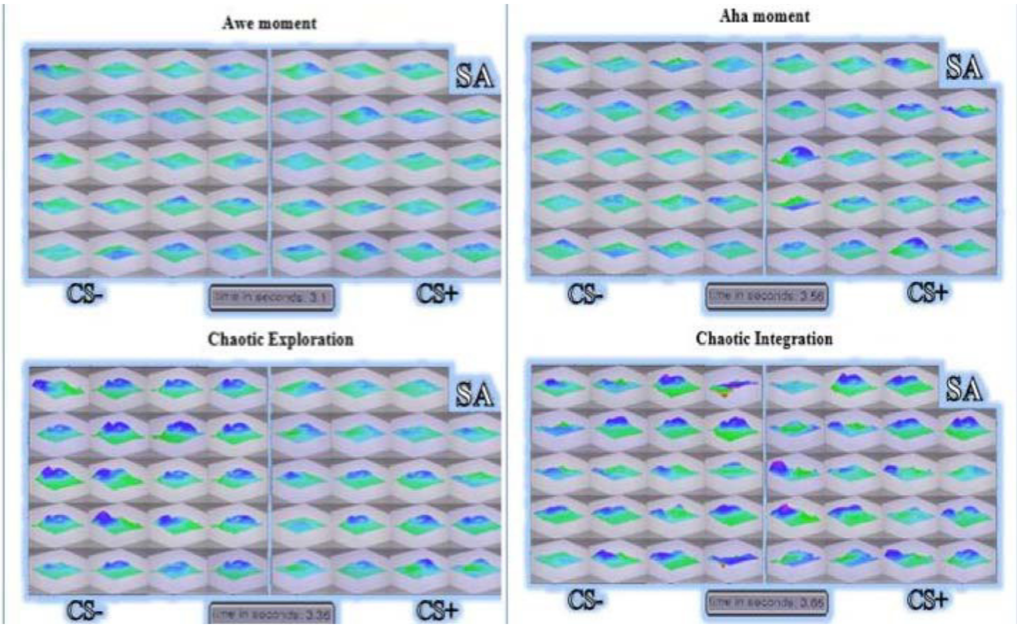

Figure 2. Movie-frame illustrations of Type 3 Movies. The 8x8 Spatio-Temporal patterns for the SA over the Gamma band (30 Hz – 36 Hz), for the 39 runs for Awe, Chaotic Exploration, Aha, and Chaotic Integration.

Figure 2 shows a **Type 3** movie-frame, displaying the 39 experiments of four of the five stages of the cycle for the SA over the gamma band. Observe the different behavior of the SA in the different stages of the different behavior between CS+ and CS- experiments within each stage of the cycle. For the ***Aha moment*** we can observe high synchronization and low signal amplitudes for the 39 runs, CS+ and CS-. In the ***Chaotic Exploration*** moment we observe a desynchronization period followed by a strong rise of the SA in large regions of the spatial array. In the ***Aha moment*** illustration (Fig. 2) we can also observe the tendency towards synchronization and the drop of amplitudes reflected in the SA. At this moment the CS+ and CS- experiments show some minor differences in behavior, which may lead us to conjecture that there are different delays or amplitude magnitudes associated with the different type of stimuli (CS+ and CS-).

Figure 3 is a movie-frame illustration for **Type 2** movies showing the four indices for the gamma band. In this movie we can observe the "null spikes" in $Log_{10}AA$, which are somehow related to the frequency dispersions of the IF, Fig. 3a. This is followed by an increase in analytic amplitude around a certain region of the array as shown in both the $Log_{10}AA$ and SA indices. It is important to observe that this increase in amplitude is associated with a high degree of synchronization across the 8x8 array reflected in very low dispersions of the IF, as shown in Figure 3b. We can also see very clearly how the region where the "null spike" takes place in the 8x8 array (as observed in $Log_{10}AA$), is the same as where the frequency dispersion increases dramatically (Figure 3a).

With the **Type 2** movies it is very easy to view the tornado-like patterns of behavior in the SA both 2D and 3D. These tornado-like patterns are associated with the increase in amplitude at regions showing low frequency dispersions. Generally speaking, we have observed the sequential relationship of events between the null spike, the frequency indeterminacies (associated with phase cones), the rise in amplitudes and the tornado like patterns. With the **Type 3** movies it is possible to have a first impression of any distinctions between CS+ and CS- patterns that could be classifiable. There are important features about the synchronization-desynchronization associated with the cycle of creation of knowledge and meaning and the sequential events that take place for different indices that can also be observed in the **Type 1** movies. This type of display shows how the tornado like patterns behave across bands, where for the gamma and beta bands, the tornados move faster than for alpha and theta while the tornado's direction switches from clockwise to anticlockwise, simultaneously across bands.

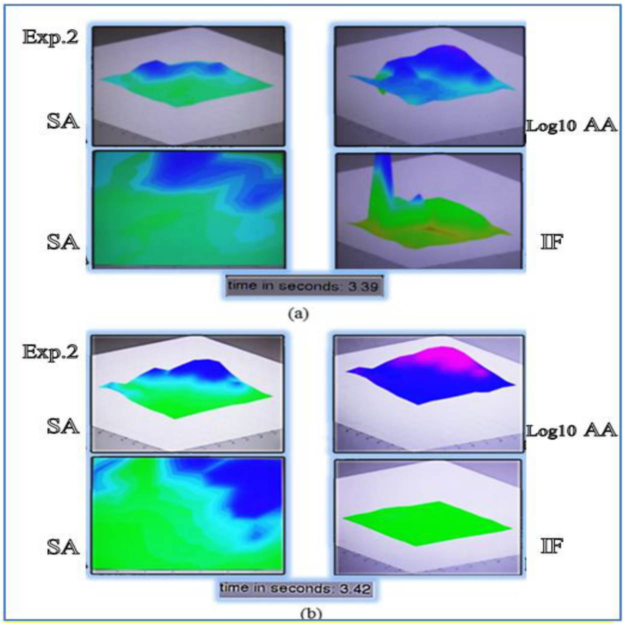

Figure 3. Movie-frame illustrations of **Type 2** Movies. The 8x8 Spatio-Temporal patterns for the 4 indexes in gamma band (**Type 2**) for a CS+ experiment #2 (a) time 3:39 (b) time 3:42.

4. Discussions and Conclusion

The methodology that has been presented here has successfully allowed us to display large quantities of data for the study and understanding of the neural correlates of higher cognitive functions. The Art of Encephalography has opened a door to the important role of visual inspection and training on ECoG and EEG signals, giving us a new perspective on the processes underlying cognition. This methodology also comes with the opportunity of building a data bank of brain dynamics movies, which can be of great support in learning and understanding the way the brain creates knowledge and meaning. It is an important step towards the way the cognitive neuroscience community introduces people from other disciplines and practices to a broader understanding of the brain to bridge the gap between physics and neurobiology, for example, in understanding brain field dynamics and consciousness and facilitate tools and biofeedback systems for people to learn interactively what is meaningful to them by means of movie displays. We are convinced that quantitative approaches hand in hand with Freeman's cinematic ideas (Freeman W. J., 2015) will greatly complement the learning process about brain dynamics taking good advantage of the complementarity of qualitative and quantitative analysis about the nature of the structure of meaning.

Future applications encompass measuring EEG activity in humans to attempt explaining brain patterns while in relaxation, meditation, and other coherent states mediated by breathing, in contrast with stressful mental activity. The direct benefit of producing movies in this unique way is that it allows for simultaneous study and artful visualization of large quantities of data, improving dramatically both the understanding of brain dynamics and the efficiency of data analysis. Various experimental approaches will be used to solve these challenging issues. We hope our findings based on ECoG analysis motivate further studies towards the identification of neural correlates of cognition and awareness experience through the integration of various experimental paradigms.

Acknowledgments

Experimental data are from the Freeman Neurophysiology Laboratory, Division of Neuroscience, University of California at Berkeley. We owe our gratitude to The Embassy of Peace in New Zealand, Whitianga, particularly to Maria for her invaluable altruistic technical support in the production of the movies. Partial support is from NSF grant DMS13-11165.

References

Barrie, J. M., Freeman, W. J., & Lenhart, M. (1996). Modulation by discriminative training of spatial patterns of gamma EEG amplitude and phase in rabbits. *J. Neurophysiol.*, 76, 520–539.

Barsalou, L. (2008). Grounded Cognition. *Annual Rev. Psychol*, 59: 617–645.

Borges I, J., Filomena V, M. V., Faoro M, A., & Perez de Pernia, E. (1985). *Electroencefalografia Clinica – Patrones Y Terminologia.* Caracas: Universidad Centra De Venezuela.

Davis, J. J. (2009). *The Brain of Melchizedek: A Cognitive Neuroscience Approach to Spirituality (Thesis, Master of Science).* Dunedin: University of Otago.

Davis, J. J. (2015, June 7). *Brain Dynamics-EEG Movies*. Retrieved from The Science of Peace website: http://thescienceofpeace.weebly.com/eeg-movies.html

Davis, J. J., & Kozma, R. (2012). Analysis of Phase Relationships in ECoG Using Hilbert Transform and Information-Theoretic Measures. *Proc., IJCNN2012/ WCCI2012.* Brisbane: IEEE Pr..

Davis, J. J., & Kozma, R. (2013). Creation of Knowledge & Meaning Manifested via Cortical Singularities in Cognition. *Proc. 2013 IEEE Symposium Series on Computational Intelligence (SSCI) Cognitive Algorithms, Mind, and Brain (CCMB), SS-0923,* IEEE Press.

Davis, J. J., Kozma, R., & Freeman, W. J. (2013). Neurophysiological evidence of the cognitive cycle and the emergence of awareness.". *Int. Conf. Awareness Sci. & Tech. iCAST2013.*, IEEE.

Del Cul, A., Baillet, S., & Dehaene, S. (2007). Brain dynamics underlying the nonlinear threshold for access to consciousness. *PLOS Biology*, 5(10), 2408-2423.

Freeman, W. (1975). *Mass action in the nervous system.* New York,: Academic Press.

Freeman, W. J. (1999). *Consciousness, Intentionality and Causality. In: Reclaiming Cognition: The Primacy of Action, Intention and Emotion. Núñez, R., Freeman, W. (eds.).* AP, Bowling Gr.

Freeman, W. J. (2000). Analysis of spatial patterns of phase in neocortical gamma EEGs in rabbit. *J. Neurophysiol* , 84, 1266–1278.

Freeman, W. J. (2015, June 2). Retrieved from Mass Action in the Nervous System website: : http://soma.berkeley.edu/

Freeman, W. J., Kozma, R., & Vitello, G. (2012). Adaptation of the Generalized Carnot Cycle to Describe Thermodynamics of Cerebral Cortex. *Proc. IEEE World Congress Comp. Int.l WCCI/IJCNN 2012* (pp. pp. 3229-3236). Brisbane: IEEE Press.

Freeman, W. Quiroga, R. (2012). *Imaging Brain Function with EEG: Advanced Temporal and Spatial Analysis of Electroencephalographic Signals.* Springer Verlag.

He, B., & Raichle, M. E. (2009). The fMRI signal, slow cortical potential and consciousness. *Trends in Cogn. Sci.*, 13(7), 302-309.

Hild, K. E., Erdogmus, D., Torkkola, K., & Principe, J. C. (2006). Feature extraction using information-theoretic learning Pattern Analysis and Machine Intelligence . *IEEE Transactions*, 28(9), 1385-1392.

Koch, C., & Tononi, G. (2011). A Test for Consciousness. *Sci. American*, 304(6), 44-47.

Kozma, R., & Freeman, W. J. (2002). Classification of EEG Patterns Using Nonlinear Neurodynamics and Chaos. *Neurocomputing*, 44-46, 1107-1112.

Kozma, R., Davis, J. J., & Freeman, W. J. (2012). Synchronized Minima in ECoG Power at Frequencies Between Beta-Gamma Oscillations Disclose Cortical Singularities in Cognition. *Journal of Neuroscience and Neuroengineering*, 1(1), 13-23..

Thompson, E., & Varela, F. (2001). Radical Embodiment: Neural Dynamics and Consciousness. *Trends in Cogn. Sci.*, 5, 418–425.