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Brain Maturation Changes Characterized by Algorithmic Complexity (Lempel and Ziv Complexity)

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Abstract. Recent experimental results suggest that basal electroencephalogram (EEG)changes reflect the widespread functional evolution in neuronal circuits, occurring in chicken brain during the "synapse maturation" period, between 3 and 8 weeks' posthatch. In present work a quantitative analysis based on the Algorithmic Complexity (Lempel and Ziv Complexity) is performed. It is shown that this complexity presents a peak at week 2 posthatch 2, and a tendency to stabilize its values after the week 5 posthatch.

Keywords: EEG; brain maturation; Lempel-Ziv complexity
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INTRODUCTION

Literature on the use of the EEG in the chicken is not extensive. Research efforts have largely concerned the use of the EEG either as an indicator of the general integrity of the nervous system or as a measure of specific brain states, such as sleep cycles and other EEG rhythm defined states. In those studies using the EEG as a functional integrity measure of the chicken nervous system, a major interest has been to plot the embryonic development of the chicken brain. Synapse formation in the chicken brain occurs most rapidly around the time of hatching and it is complete by 10 to 14 days posthatch [1]. Subsequently, the immature synapses and neurons gradually attain adult ultrastructural and biochemical properties. These changes occur in the period between 3 and 8 weeks posthatch, during which neuronal circuits become fine-tuned, and has been termed the "maturation period" by Rostas, [2] .

It may be assumed that these synaptic connections are maturing in response to both internal and environmental stimulation. In a previous work scalp-applied recording electrodes were used to monitor changes in chicken's basal EEG patterns during posthatch development [3]. Frequency spectra produced by Fast Fourier Transform (FFT) show biphasic morphology in all chickens with peaks at about 7 Hz and 26 Hz. Changes in the lower frequency band show progressive development and provide a possible index of brain development. Both amplitude and dominant spectral frequency decrease between weeks 3 and 8 posthatch, reaching adult levels between weeks 5 and 7. The results suggest that modifications of basal EEG reflect the widespread functional changes in neuronal circuits occurring in chicken during the "synapse maturation" period, between 3 and 8 weeks' posthatch. In the present work a quantitative analysis using the Lempel and Ziv Complexity [4, 5] of chicken EEG basal activity is presented. In particular, it shows that the proposed complexity quantifier presents a peak at week 2 and also a tendency to stabilize its value after week 5, in agreement with the previous description of synapse maturation.

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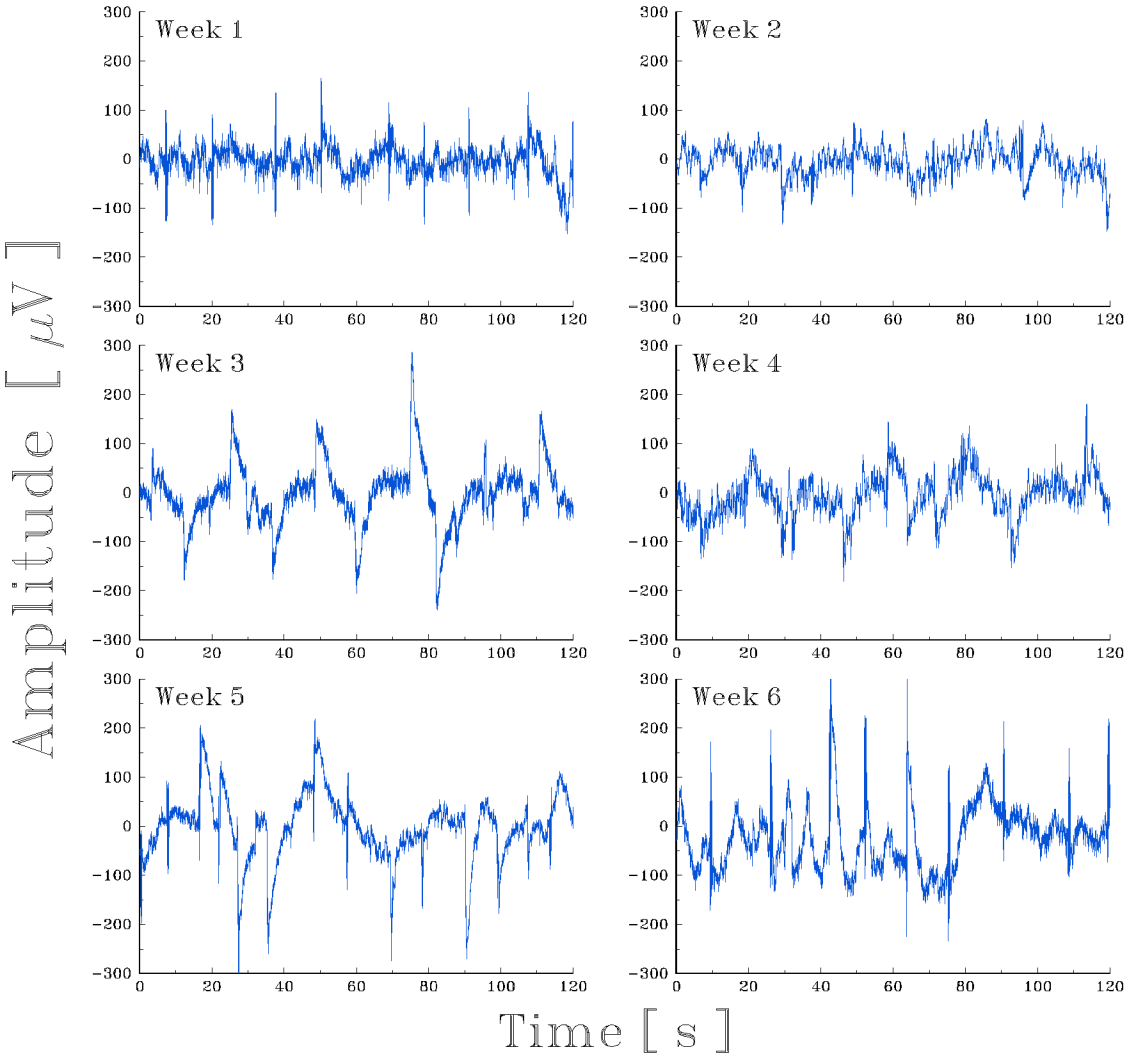

FIGURE 1. Original EEG time series at left frontal electrode (LF) corresponding to *Bird #1* for the 6 weeks' posthatch.

EXPERIMENTAL DATA AND ARTIFACT REDUCTION

Twenty four chickens (*Gallus domesticus*) reared from hatching were the subjects in this experiment. All birds had free access to food and water throughout the experiment. The birds were reared initially in incubation boxes and then transferred to holding cages maintained at a constant temperature ($21^{\circ}C$) with a $12:12\ hr$ light:dark cycle.

Continuous EEG recordings ($0.1-100\ Hz$ with a $50\ Hz$ notch filter) were made using small ($6\ mm$) gold cup electrodes attached to the scalp with collodion glue and filled with electrode gel. The signal was sampled at a rate of $128\ Hz$, passed through amplifiers, and stored directly on computer. The total length of each record is 16368 *data*. Data acquisition was controlled by Strawberry Tree software. Four electrodes were placed over left and right frontal (LF and RF), and left and right posterior (LP and RP) areas of the scalp with an additional reference electrode placed at the back of the head. EEG recordings where taken at Day 7 posthatch and then each week for 6 weeks. For additional details of the acquisition protocol see [3].

In animals and also in human developmental changes are correlated with the presence of different rhythms. The raw EEG provides evidence of developmental change because there is a greater variance shown in the typical 1-week-posthatch recording (see Fig. 1.a) compare with the typical 6-week-posthatch recording (see Fig. 1.f) From Fig. 1 it

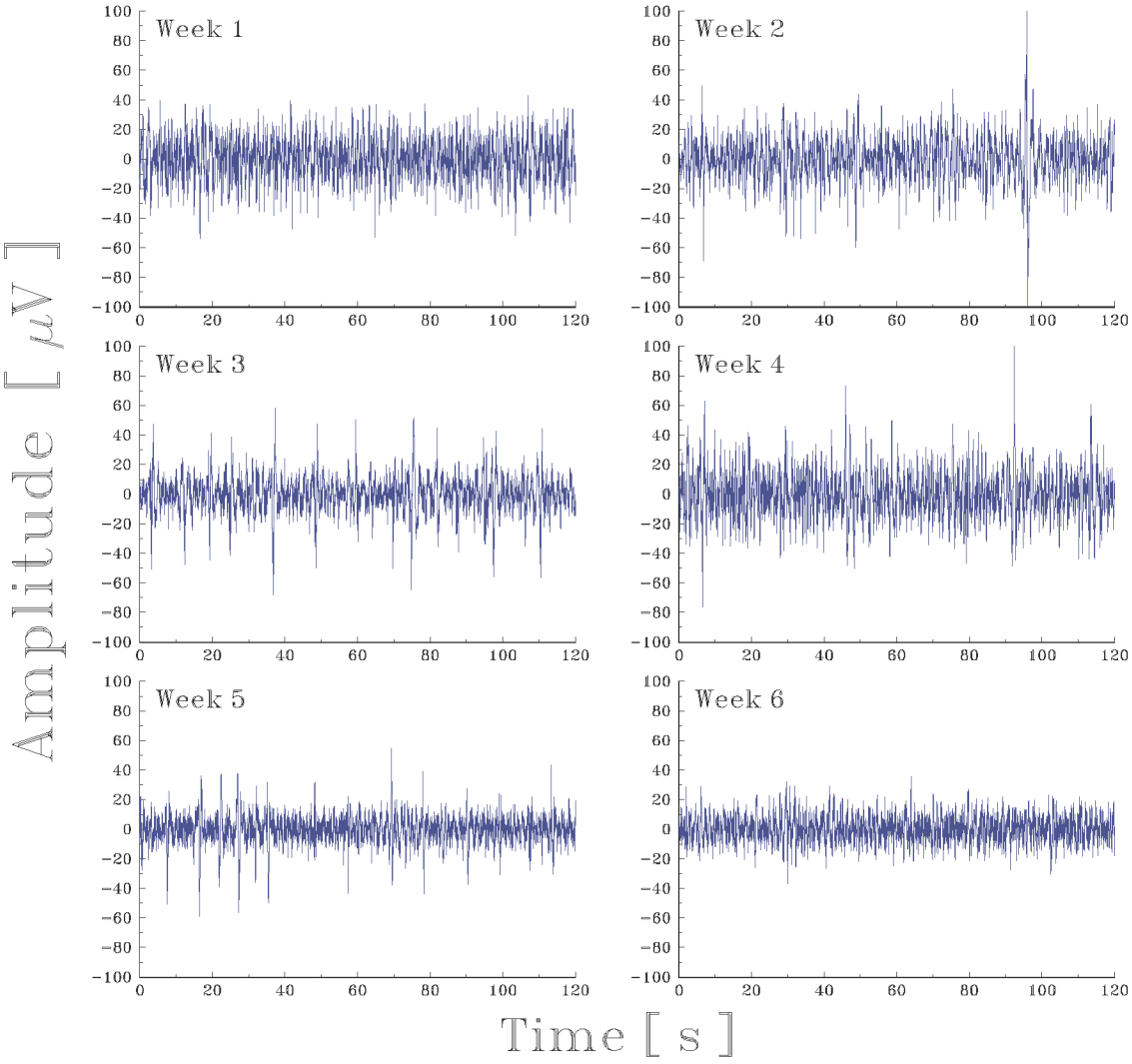

FIGURE 2. Cleaning EEG time series at left frontal electrode (LF) corresponding to *Bird #8* for the 6 weeks' posthatch.

is clear that these EEG signals are nonstationary. They also present artifacts due to saccadic eye movements [3]. In order to avoid these problems and improve a subsequent quantitative analysis, each signal was pre-processed using a methodology based on Wavelets (for procedure details see [6]).

The procedure consisted in two steps:

- The Discrete Orthogonal Wavelet Transform of the signal was obtained considering $J_{max} = -10$ wavelet resolution levels with spline cubic mother wavelet. After that a cleaning and stationary signal was obtained by reconstruction (inverse wavelet transform) using the resolution wavelet levels corresponding to the frequency range $0.5 - 32.0\ Hz$ (see Fig. 3.b).
- Both the wavelet frequency bands at which the saccadic movement frequencies appears, and their time localization were identified. The corresponding wavelet coefficients were reduced in order that their contribution were below the noise-signal level. Finally the corresponding frequency band was reconstructed and the complete filtered signal was obtained by superposition of the all wavelet reconstructed frequency bands (see Fig. 3.c).

As an example, in Figs. 1 and 2, the raw and clean EEG signals corresponding to the *Bird #8* are shown.

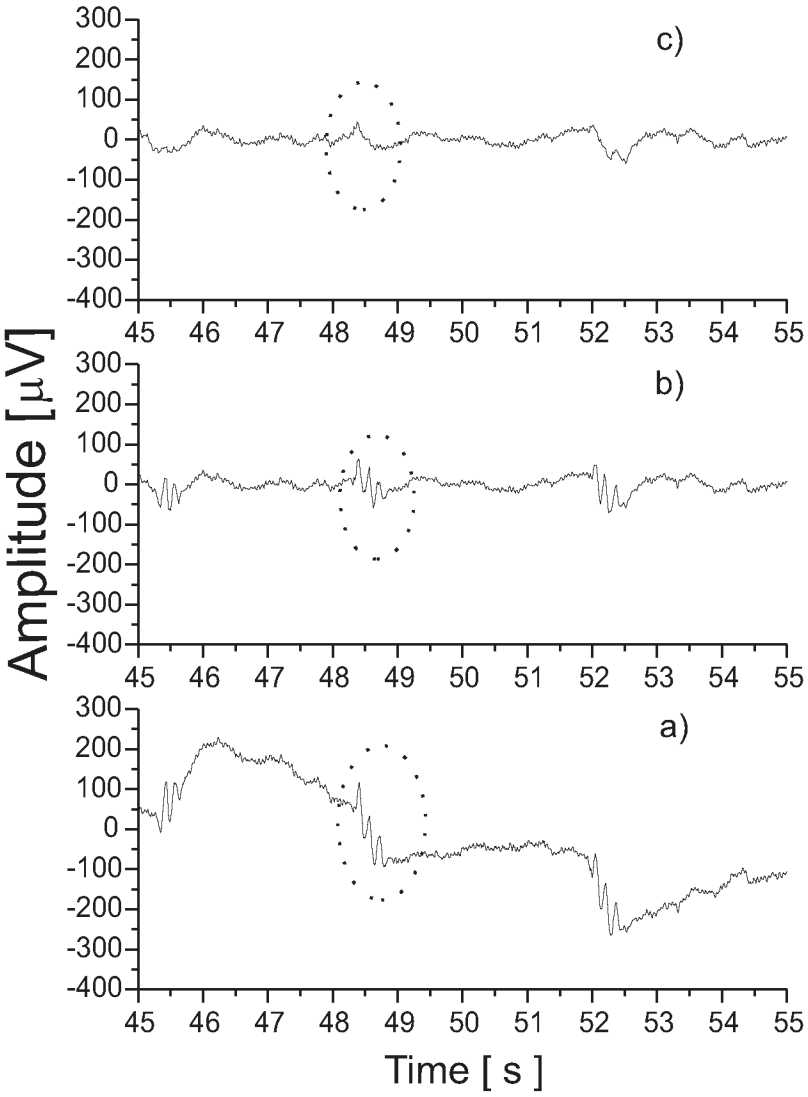

FIGURE 3. Cleaning EEG time series process: *a)* Original time series; *b)* Stationary wavelet reconstructed time series for the frequency range $0.5 - 32.0\ Hz$; *c)* Cleaning EEG time series, without saccadic artifacts. The saccadic artifact are marked with dots line.

LEMPEL AND ZIV COMPLEXITY

The Algorithmic Complexity has shown its ability to distinguish evolutionary characteristics in many fields. For a string of characters it is defined as the length in bits of the smallest program that produces the string as output [7]. The problem with this definition is that it is impossible, even in principle, to find such a program. Nevertheless, the zippers or file compressors are algorithms conceived to do that job at least approximately. The Lempel and Ziv algorithm is used for most zippers and it is one of the best known file compressors [4, 5].

Let l^U_{ijk} be the string length of the time series for bird i, in week j, electrode k (superscript U for *unzipped*). Let l^Z_{ijk} be the corresponding zipped string length (superscript Z for *zipped*). The *Zipping Complexity* for this particular time series is given by:

$$c_{ijk} = \frac{l^Z_{ijk}}{l^U_{ijk}} \,. \tag{1}$$

In the case of Zipping Complexity it is also necessary to correct the effect of sampling rate and epoch length on the

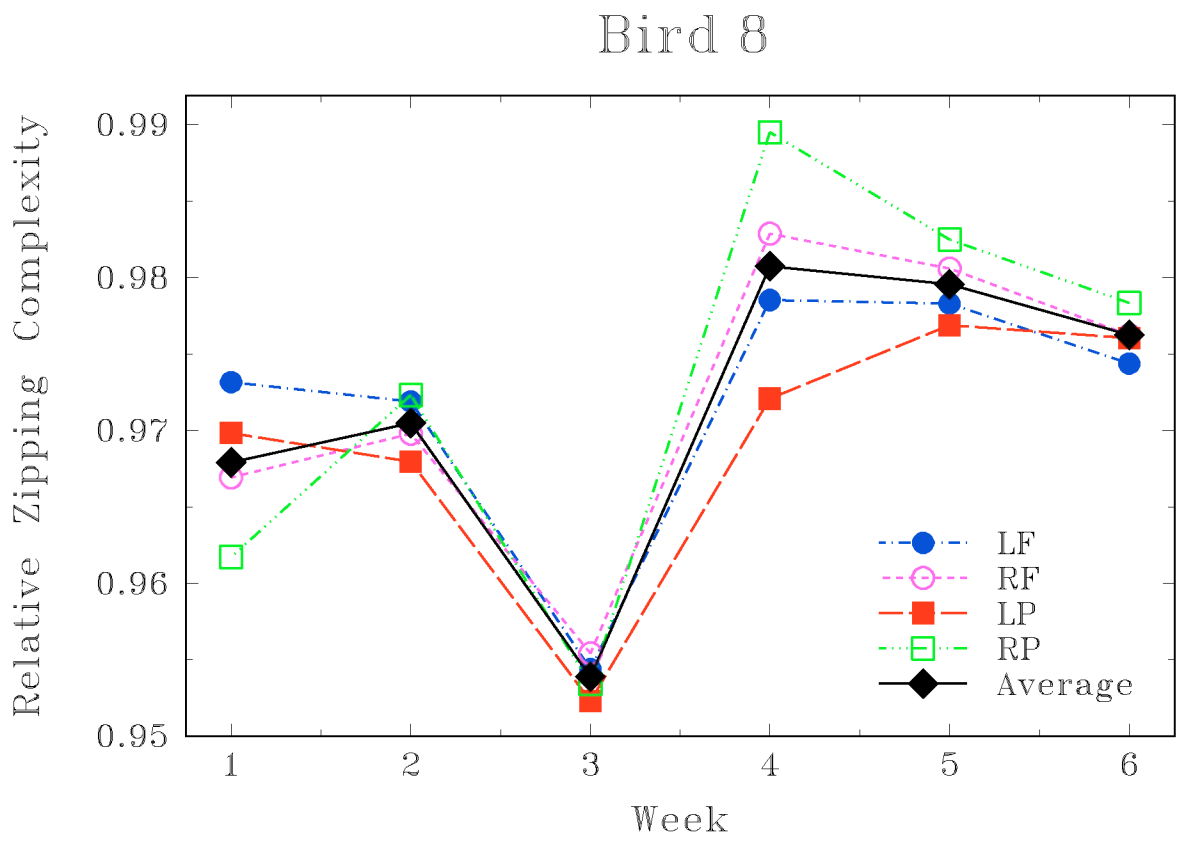

FIGURE 4. Relative Zipping Complexity for *Bird #8* at LF, RF, LP, RP electrodes and average electrode, for the 6 weeks' posthatch.

algorithmic complexity. These effects were studied by P. E. Rapp and co-workers in [8]. This drawback is solved using surrogates: an ensemble of random nondeterministic data sets with the same mean, variance and power spectrum as the experimental time series. The quantifier proposed by Rapp *at al.* is *the Relative Zipping Complexity*:

$$C_{ijk} = \frac{c_{ijk}}{\langle c^{(s)}_{ijk} \rangle} , \tag{2}$$

where $\langle c^{(s)} \rangle$ corresponds to the Zipping Complexity mean value over all considered surrogates of the original time series. We used a hundred surrogates in our calculations.

There are several methods to generate surrogate data sets with the conditions stated above. In the present work we use the algorithm proposed by Henry, Novell and Camacho [9]. Essentially the method consists on the following steps:

- Evaluate the time series discrete Fourier transform Z_{ijk};
- Add a random phase φ to obtain $Z'_{ijk} = Z_{ijk} \exp \varphi$;
- Construct the inverse Fourier transform of Z'. This is one surrogate time series.

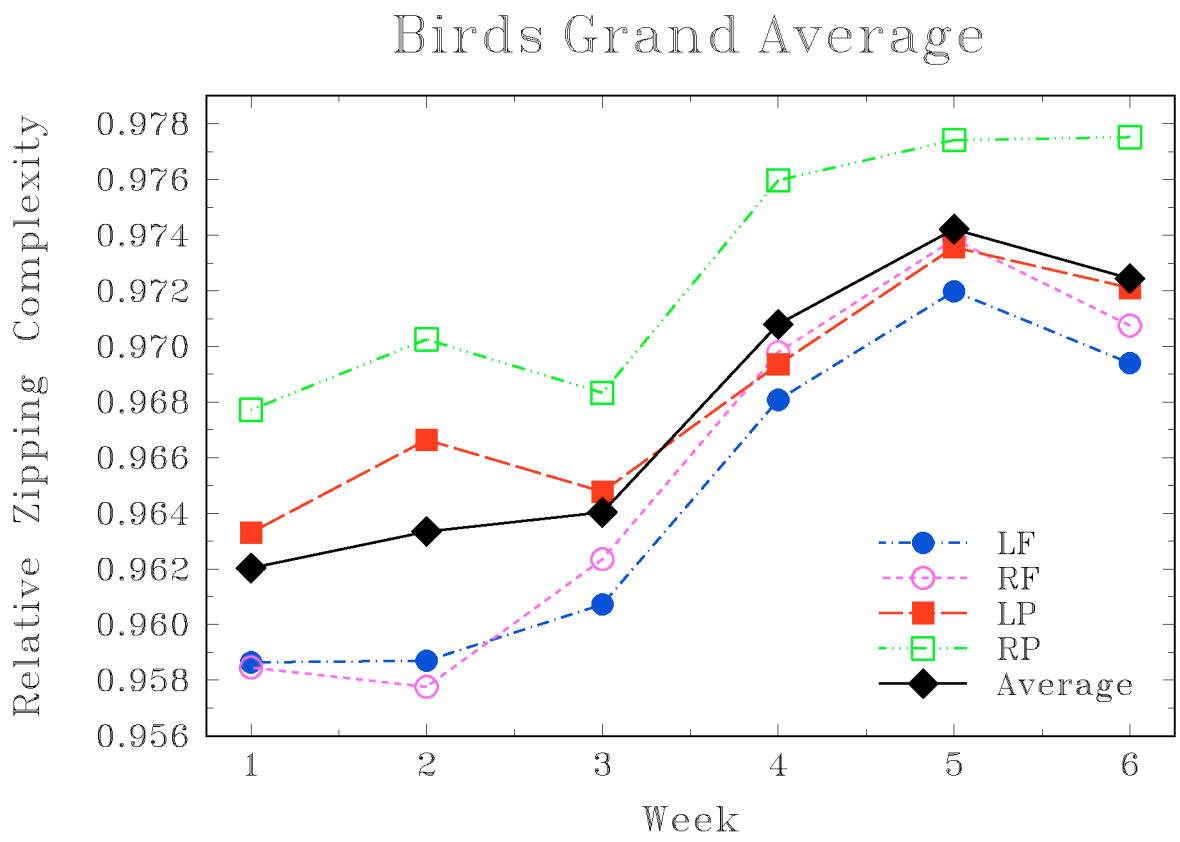

FIGURE 5. Grand Average Relative Zipping Complexity for the 24 birds at LF, RF, LP, RP electrodes and average electrode, for the 6 weeks' posthatch.

RESULTS AND DISCUSSION

As explained above, in the case of time series studied in this paper a pre-processing was required to eliminate undesired frequencies produced by a repetitive motion (saccadic movements) typical of the studied birds. This preprocessing was not straightforward (it can not be done with band pass filters) and was the object of a previous paper [6]. The cleaning EEG data sets were then characterized by means of their Relative Zipping Complexity (RZC) measure C.

In Figs. 4 and 5 the Relative Zipping Complexity evolution (in weeks) for the *Bird #8* and the corresponding Grand Average value over 24 *Birds* are shown for each electrode. In the same figures, average over all electrodes are also displayed.

The RZC data obtained show a distinctive pattern of change during development through the synapse formation period (up to 3 weeks' posthatch) and the synapse maturation period (from 2 to 6 weeks' posthatch). It is interesting to note that the RZC present oscillatory behavior for a given Bird, however the mean RZC increases with time during weeks 3 to 5, showing a tendency to stabilize its value in the last weeks. Note also, that this behavior is associated with the "maturation period" described by Rostas and co-workers [2]. A pick appear in the RZC at week 2 (see Fig. 5) which can be associated with the complete synapse formation [1]. The EEG analysis for each individual electrode showed that the same developmental pattern occurred at each site but greater values are observed at posterior sites. Also some differences between hemisphere are founded. Whether the latter finding reflects the bilateral asymmetry of

brain function, which underlies many behaviors in chickens, remains to be established. In summary we can conclude that a good quantification of brain maturation changes can be done by the Relative Zipping Complexity and results are in good agreement with previous spectral and morphological studies [3].

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