ERP and adaptive autoregressive identification with spectral power decomposition to study rapid auditory processing in infants

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***Abstract*—The ability to process rapidly-occurring auditory stimuli plays an important role in the mechanisms of language acquisition. For this reason, the research community has begun to investigate infant auditory processing, particularly using the Event Related Potentials (ERP) technique. In this paper we approach this issue by means of time domain and time-frequency domain analysis. For the latter, we propose the use of Adaptive Autoregressive (AAR) identification with spectral power decomposition. Results show EEG delta-theta oscillation enhancement related to the processing of acoustic frequency and duration changes, suggesting that, as expected, power modulation encodes rapid auditory processing (RAP) in infants and that the time-frequency analysis method proposed is able to identify this modulation.**

I. Introduction

The ability to process and categorize rapidly-occurring auditory stimuli is a critical component of language acquisition and development [1]. The scientific literature suggests that deficit in these abilities could be one of the risk factors for language impairments, affecting speech perception, language comprehension/production and reading ability [2]. For these reasons RAP has begun to be studied in infants, mainly using the ERP technique, revealing association with later literacy skills [3,4]. More recently, the idea that also neuronal oscillatory mechanisms may play a role in auditory cortical development and information processing has been raised, and event related brain oscillations have also begun to be investigated [5,6]. Oscillatory processes provide, in fact, mechanisms for organizing neuronal activity at the neurons population level and play a role in many aspects of ERP morphology [7]. Infant brain event related oscillations have been studied using wavelet transform [5] and Besa Inc. Temporal Spectral Evolution (TSE) [6] in auditory Mismatch Response (MMR) oddball paradigms with infrequent deviant tones differing in fundamental frequency. In this paper, we examine RAP in healthy infants using both time domain analysis and time-frequency domain analysis. For the latter, we propose a method that combines the use of AAR identification and spectral power decomposition. We think that this method, previously used for studying movement-related activity in adult scalp EEG signals [8], can be applied to examine infant brain oscillations undergoing the ERP phenomena, allowing measurement of time-frequency event related power and frequency modulation. Moreover, the perception of rapid auditory changes is investigated not only regarding frequency sound characteristics but also duration characteristics that are equally important in language processing.

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II. Methods

A. Experimental protocol and data acquisition

A group of 10 healthy infants (7 female, mean age 6 months, 11 days, *SD* = 10 days) participated to this study. Informed consent was obtained from parents prior to their child's inclusion in the study. The project was approved by our Scientific Institute ethical committee.

The stimulation paradigm is a passive oddball paradigm with a standard (STD) stimulus (80% probabilities, n=960) and two deviant stimuli (10% probabilities, n=120), presented in a semi-randomized way with the constraints of at least 3 STD stimuli between 2 deviant sounds. The stimuli are complex tone pairs separated by 70 ms interval. The first tone is the same for all the 3 conditions (100 Hz, 70 ms), whereas the second tone is equal to the first one for the STD condition and differs in the two deviant conditions: frequency deviant (DEVF, 300Hz, 70 ms) and duration deviant (DEVD, 100Hz, 200 ms). The offset-to-onset inter trial interval randomly varies from 700 to 900 ms.

Auditory ERPs were recorded from 60 scalp sites (sampling frequency = 250 Hz, online bandpass filter 0.1-100 Hz) using EGI recording system (Electric Geodesic, Inc., Eugene, Oregon). The vertex electrode was used as the online reference electrode, whereas offline Current Source Density (CSD) was calculated applying scalp surface Laplacian estimates to the EEG/ERP signals, obtaining reference-free data [9,10]. After recording, data were exported to a MATLAB (Mathworks, Natick, MA) compatible format. EEG signals were then processed using custom scripts, EEGLAB [11], and ERPLAB (UC-Davis Center for Mind & Brain, Davis, CA) running in the MATLAB environment.

B. Analysis of ERP data

Continuous EEG data were offline bandpass filtered 0.5-30 Hz. Channels with high impedance (>50KΩ) or with visually evident noise were interpolated with a spherical

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spline. No more than 10% of channels were interpolated (average: 3) and none of them corresponded to the channels considered for further analysis. The continuous EEG was then segmented according to the stimulus type (pre-deviant STD, DEVF and DEVD) in 900 ms epoch length (100 ms before stimulus presentation and 800 ms afterward). In addition, the 100 ms pre-stimulus segment was used for baseline correction. Bad EEG epochs were identified using two automatic criteria and visual inspection. First, a moving window (200 ms width, 50 ms step) was used to identify segments containing signals with voltage difference greater than 150μV. Second, epochs corrupted by muscle activity were selected using spectral estimates (trial spectra deviating from the mean by +25 or -100 dB in frequencies over 20 Hz) [12]. Bad EEG segments were rejected and a minimum of 60 artifact-free trials was used for averaging ERPs (average:125, 69 and 69 epochs for STD, DEVF and DEVD, respectively). MMRs were obtained subtracting the pre-deviant STD ERP wave from the DEVF ERP wave (MMR_F) and the DEVD ERP wave (MMR_D). Latencies and amplitudes of the two MMRs were then measured within the window of 350-550 ms for the MMR_F and 420-620 ms for the MMR_D. Analyses conducted over two bilateral frontal sites (F5, F6) are reported here.

C. Time-frequency analysis

The study of event-related spectral evolution over time was conducted relative to the EEG signals recorded from the two frontal sites already considered in time domain ERPs (F5, F6). For time-frequency analysis, EEG data were bandpass filtered 1-30 Hz, with the aim to eliminate the very low frequency components that could affect our results. Data were also down-sampled at 125 Hz, rejecting redundant information that would have uselessly made the AAR identification more laborious. The scalp EEG signals were modeled using an AAR model of the form:

$$y(t) = \varphi(t)^T \Theta(t) + w(t), \tag{1}$$

where $\varphi(t)=[y(t-1),\ldots,y(t-n)]$ is the observations vector, $\Theta(t)=[a_1(t),\ldots,a_n(t)]$ is the time-varying autoregressive parameters vector, $w(t)$ is a white noise (mean=0, variance=σ^2) and n is the model order. The parameter vector $\Theta(t)$ is identified from the data using the recursive least square method combined with the exponential forgetting factor (λ, $0 \le \lambda \le 1$) [8], obtaining the update of the model by means of the following equations:

$$\begin{cases} \Theta(t) = \Theta(t-1) + K(t)\,\varepsilon(t) \\ K(t) = P(t-1)\,\varphi(t) \\ \varepsilon(t) = y(t) - \varphi(t)^T\,\Theta(t-1) \\ P(t) = [1/\lambda]\,\{P(t-1) - [P(t-1)\;\varphi(t)\;\varphi(t)^T\;P(t-1)] \\ \qquad [\lambda + \varphi(t)^T\;P(t-1)\;\varphi(t)]\}^{-1}, \end{cases} \tag{2}$$

where $\varepsilon(t)$ is the priori prediction error, $K(t)$ is a time-varying gain and $P(t)$ corresponds to the inverse covariance matrix of the signal. The model order was set to n=11 and it was selected applying the Akaike's Information Criterion to a subset of the data and then choosing the average order obtained [8,13]. The exponential forgetting factor was selected minimizing the Relative Error Variance [14], calculated on a subset of the data too, and it was set to λ=0.95, that means a memory length of N=20 samples. After the AAR identification was applied to the signal, the resulting time-varying parameters vector was segmented according to the artifact free 900 ms epochs selected during ERP analysis and then synchronously averaged across trials for the 3 conditions (pre-deviant STD, DEVF and DEVD) obtaining 3 average event related AAR models. These resulting models, containing all the time-frequency spectral information of the signal, underwent spectral power decomposition through the residual method, which identifies the power and frequency characteristics of each spectral component by mean of the position and the residual of AAR model poles [15]. The spectral decomposition was performed at every time instant t of the average event related AAR models, so that each real pole i or pair of complex poles i was characterized by a time-dependent power value $P_i(t)$ and a time-dependent frequency value $F_i(t)$.

First of all, we studied time-frequency event related spectral information for the three experimental conditions and we calculated the time-frequency power differences in response to infrequent minus frequent tones: DEVF–STD and DEVD–STD. Then we investigated the event-related power modulation by means of residual spectral decomposition, concentrating our attention in poles related to delta (1-4 Hz) and theta (4-8 Hz) bands, previously considered in infant auditory event-related time-frequency analysis [5,6]. In particular, based on the lack of agreement in identifying frequency boundaries of infant EEG rhythms [16] we decided to investigate the power modulation selecting individually tailored bands on the basis of the observed time-frequency power distribution. The selected bands are all in the range 1-7 Hz. Considering these frequency bands, event-related desynchronization and synchronization (ERD/ERS) in respect to the 100 ms pre-stimulus baseline were calculated for each subject and for each condition as follow [17]:

$$ERD/ERS(\%) = [(A-R)/R] \times 100, \tag{3}$$

where R is the mean power in the baseline period and A is the vector containing the time-varying power in the 800 ms post-stimulus epoch. As suggested in [17], before calculating ERD/ERS, power values have been filtered with a moving average filter in order to smooth the data and reduce the variability. ERD/ERS time course relative to the pre-deviant STD condition was then subtracted to the ones of the two deviant conditions obtaining ERD/ERS time course differences (DEVF–STD and DEVD–STD). Finally, the greatest positive peak of the resulting waves, within the window of 300-700 ms, was detected and its amplitude and latency were calculated.

D. Statistical analysis

One sample Wilcoxon signed rank test was used to evaluate the statistical significance of peaks amplitude both for MMR and ERD/ERS difference peaks. Friedman test, eventually followed by Wilcoxon-Mann-Whitney test, was performed to assess laterality or condition differences latencies and amplitudes for the considered peaks.

III. RESULTS

A. ERP responses

ERPs analysis shows, in both the channels considered (F5, F6) and for both deviant stimuli, a clear MMR (Fig. 1) occurring at about 423 ms (*SD* = 41) for the MMR_F and about 518 ms (*SD* = 43,5) for the MMR_D. Amplitude and latency median values and percentiles relative to the MMRs in both channels are reported in Table I. All amplitude values are significantly different from the zero median ($p<0.01$), underlying the reliability of the response. Friedman test applied to peak amplitude relative to both conditions and both channels indicate a lack of laterality or condition effect ($p>0.05$), even if the amplitudes in the right hemisphere seem to be slightly greater than in the left ones. Whereas, the same test applied to peak latencies shows a significant effect ($p<0.01$). Investigating this effect using a Wilcoxon-Mann-Whitney test for the comparison of two dependent samples we find that MMR_D latency is longer than the MMR_F ones both on the right and on the left hemisphere, revealing a condition effect ($p<0.01$).

B. Event-related time-frequency response

The grandaverage of time-frequency spectral difference between the two deviant responses and pre-deviant STD response is represented in Fig. 2, where a positive difference is clearly visible, after around 400 ms in a frequency range around 2-6 Hz, for both conditions particularly in channel F6. Median latency and amplitude of the greatest positive peak of the ERD/ERS differences between the responses to variant and invariant tones are reported in Fig. 3. In accordance with what we observed above, we found peak amplitude significantly different from the zero median ($p<0.05$), but only in the right hemisphere (ch. F6). Friedman test applied to peak latency relative to both conditions and both channels indicates that there are not effects due to laterality or condition ($p>0.05$). Whereas the same test when applied to the peak amplitudes show a significant effect ($p<0.01$). Investigating this effect using a Wilcoxon-Mann-Whitney, we found that peak amplitudes in the right hemisphere are higher than the ones of the left hemisphere for both conditions, revealing a laterality effect ($p<0.01$).

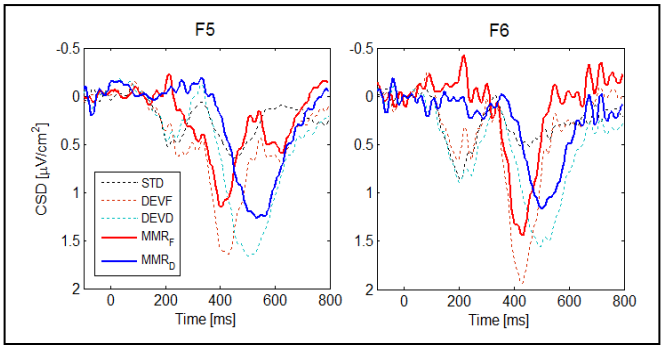

Figure 1. Grandaverage ERP waveforms. Positive down.

TABLE I. MMRS PEAKS AMPLITUDE AND LATENCY

	MMR_F				MMR_D			
	Amplitude [μV/cm²]		Latency [ms]		Amplitude [μV/cm²]		Latency [ms]	
	F5	**F6**	**F5**	**F6**	**F5**	**F6**	**F5**	**F6**
Median	1,5*	1,7*	404	432	1,3*	1,7*	526#	506#
25° perc.	0,9	1,2	394	418	1,1	1,2	496	478
75° perc.	2,0	2,2	430	439	2,1	1,8	572	519

* significant difference from zero median ($p<0.01$, One sample Wilcoxon signed rank test),
\# significant difference from MMR_F value ($p<0.01$, Wilcoxon-Mann-Whitney test).

IV. DISCUSSION

In this paper, infant RAP, and in particular the ability to detect frequency and duration changes, has been investigated using both time domain and time-frequency methods. Traditional ERP analyses were conducted revealing a bilateral MMR to both the deviant stimuli. These results replicate previous works [4,6] adding information about infant sensitivity to changes in tone duration. No amplitude condition differences were found, whereas the latency of the MMR_D peak was longer than the one of the MMR_F peak, as expected, since the difference in duration from the STD tone is not immediately recognizable (as is the difference in frequency from the STD tone). Time-frequency analyses were performed proposing a novel application of the AAR identification combined with spectral power decomposition method, previously used for studying movement-related activity in adult scalp EEG signals [8]. Results suggest the goodness of this technique to investigate brain oscillations that undergo ERP phenomena in infants. Based on recent research literature [5,6], we expected a delta-theta oscillation power increase in response to the auditory stimuli delivered. Both DEVF and DEVD conditions elicit more delta-theta oscillation enhancement than the STD condition. The oscillatory response is confined to the right cortex and a similar laterality effect has been found in [6]. This evidence suggests that the strength of synchronized neuronal activity may differ across left and right hemisphere in infants and that at around 6 month of age, a power modulation in 1-7 Hz frequency band encodes rapid auditory processing. It is interesting to note that a laterality difference does not emerge from time domain analysis.

Interesting future development involves the use of the AAR identification technique combined with spectral power decomposition in longitudinal study to investigate how event-related brain oscillations maturate in term of both power and frequency modulation. Moreover, based on the differences found in auditory processing abilities between healthy infants and infants at familial risk for language and learning disorders using ERP technique [3,4], it would be nice to investigate if these differences also involve brain oscillations.

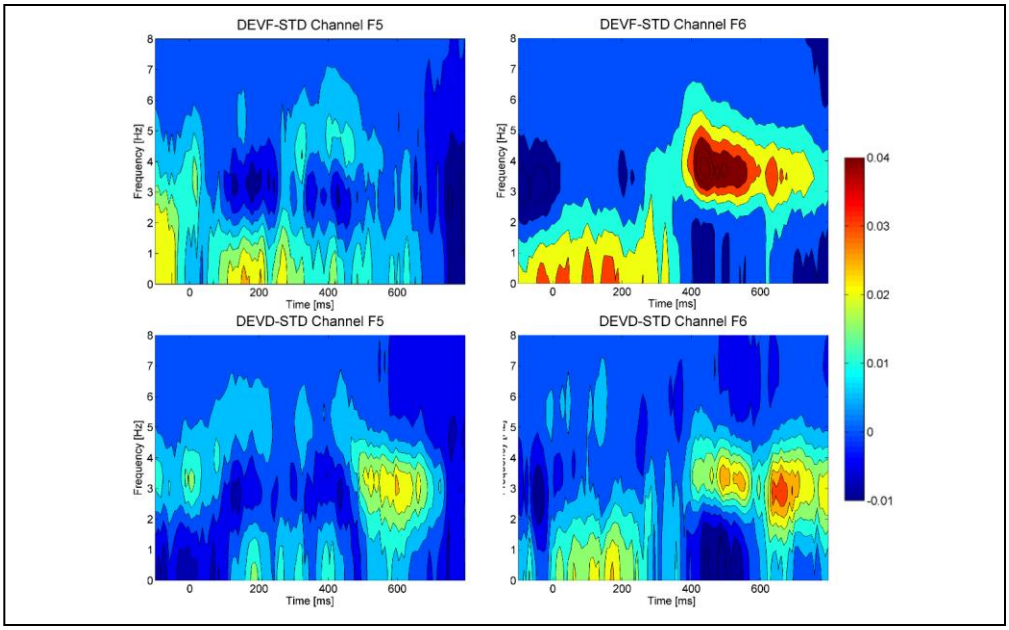

Figure 2. Grandaverage time-frequency power differences between variant and invariant stimuli response. Colours rapresent power values [$(\mu V/cm^2)^2$].

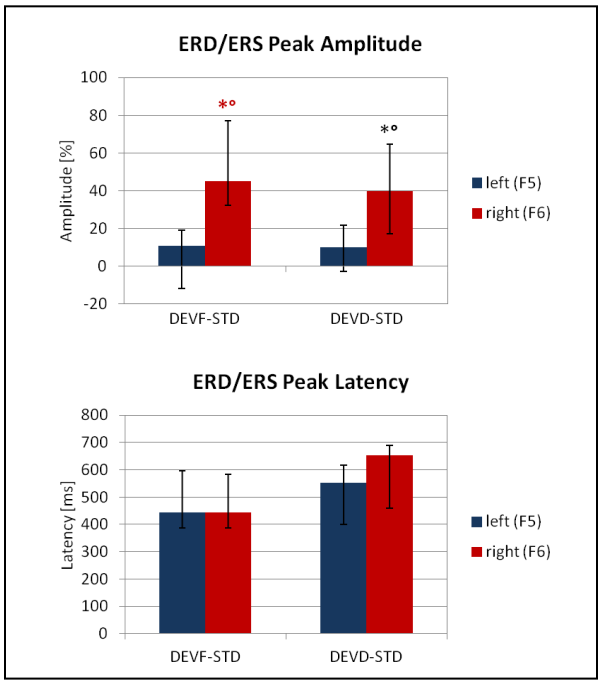

Figure 3. Peak amplitude and latency median values of the ERD/ERS difference waves. * p<0.05, * p<0.01 significant difference from zero median (One sample Wilcoxon signed rank test), ° p<0.05, ° p<0.01 significant difference from left hemisphere values (Wilcoxon-Mann-Whitney test).

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