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**An auto-regressive model for describing the auditory
component N100 of the CNV**

R.Falezza, C.Navona, A.Vaccarelli

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1. INTRODUCTION

1.1 *The Contingent Negative Variation*

In recent years, research on detection, analysis and quantification of ElectroEncephaloGraphy (EEG) connected to particular events has given substantial results. These Event-Related Potentials (ERPs), which are caused by either sensory stimuli (sensory Evoked Potentials, EPs) or endogenous cognitive stimuli or by a combination of the two, provide objective information on human brain functions, including psychological processes. The Contingent Negative Variation (CNV) or "expectancy wave", first reported by Grey Walter [WAL64], is one of the most extensively studied ERPs. It is made up of several relatively independent components, related to different neurophysiological functions. These endogenous components vary in scalp distribution, in time of appearance and in spatiotemporal overlapping patterns, depending on the sensitivity to task demands [LOV74, LOV75, KLO75, ROH76, ROH78, ROH86, GAI77, GAI86, TEC87] and on the fact that each of them is generated from different sources [MAC86, LOV87, GEV89, GEV90].

The multicomponent CNV process is sensitive to a number of psychological and behavioural variables, none of which can be singled out as an exclusive correlate. Numerous reports have linked increases in CNV activity with increasing levels of task demand and task involvement. Typically, the CNV increases in amplitude with augmented motivation and with a growth in anticipated energy output and task complexity (for reviews see: [TEC72, TEC87, MCL80, MCC81, ROH86]). It has also been demonstrated that the CNV is related to the subject's attentional level [HIL67, MCL68, TEC72, TEC87].

In studies employing relatively long 2-4 sec inter-stimulus intervals (ISI), two distinct, well-known negative components, have been distinguished. Normally, if the ISI is long enough, these components are divided by a kind of saddle. They appear after the post-warning S1¹ ERP components (for example the auditory N100, P2, N2 and P3) and can be distinguished on the basis of both temporal and topographic characteristics:

¹ S1 is the "warning signal" and S2 is the "imperative signal"

- an early component ('orienting' or O-wave), which starts around vertex (Cz), about 300 ms after S1 onset, and reaches maximal amplitude over the frontal scalp;
- a late pre-S2 component (the "expectancy", or "preparatory", E- or P-wave), maximal over the central scalp [LOV74, MCC81, ROH76, ROH78, ROH86, GAI86].

These main CNV components and reaction time to S2 have been proved to be subject to significant modification. They are sensitive to distraction or interference and to changes in behavioural alertness (level of vigilance), attention concentration, mnemonic capacity (conscious and mnestic expectation of a foreseeable event), and also to the will (motivation) to work out adequate more-or-less complex responses to imperative signals (S2), which go from merely motor to ideational, and finally to changes in personality. Like other kinds of ERPs, the CNV complex reflects the endogenous components of behaviour, including analysis of information contained in the input signal, decisional performance with selection of adequate response strategy, time estimation, preparation of motor response, etc.. Thus, it constitutes an important area of research on the different stages of cognitive stimulus processing which culminate in decision-taking. The psychological attitude of selective attention and expectancy, during which the CNV is formed, is characteristic of everyday human experience and occurs in all situations (very frequent) involving association of two successive signals; the first of these (S1) serves as a preparatory signal for S2, to which a motor response is generally made.

1.2 Auditory Evoked Potentials

The work described in this paper deals with an auditory component of the CNV complex. Many different auditory EPs can be recorded from the human scalp [STA88]. The late potentials are particularly interesting in cognitive neuroscience since they alter with changes in the psychological significance of the stimuli. The most prominent late potentials are: N100, a negative peak at about 100 msec after the onset of a sound; P2, a positive peak at about 180 msec; the sustained potential (SP), a negative baseline shift that lasts through the duration of the stimulus.

For the N100 component, intracerebral recordings are used to single out which areas of the brain are active during the scalp-recorded potentials and can describe the field-spread of these potentials [CEL76,

RIC89]. Studies of patients with brain lesions can delineate which areas are essential for generating the different scalp potentials [KNI88, PER74, SCH86]. In normal subjects, the scalp-distribution of the electric field [GIA88, PIC78b, SCH89, WOO82] or the surface distribution of the magnetic field [HAR89, WIL87] can be studied. The electric N100-wave has a widespread scalp distribution with maximal amplitude at the vertex [PIC74, WOW82]. Sometimes there is a slight asymmetry of the distribution with the amplitude being greater over the scalp contralateral to the stimulated ear [PIC78a, VAU70]. In the temporal regions, two negative waves occur with peak latencies that precede and follow the latency of the vertex N100 [PIC78b, WOL75, WOW82]. McCallum and Curry [MCC80] called these N100a and N100c to distinguish them from the vertex N100b. Näätänen and Picton [NAA87] suggested that three different intracerebral sources may contribute to these scalp-recorded waves: the first on the supratemporal plane, the second on the superior temporal gyrus, and the third in the frontal cortex. Magnetic recordings show clear evidence for activity in the supratemporal plane at the latency of the electrical N100 recorded at the vertex [HAR89, WIL87].

2. TRADITIONAL TECHNIQUES FOR AUTOMATIC EEG ANALYSIS

Automatic EEG analysis responds to a clinical demand for the definition objective methods of analysis to characterize the functioning of parts of biological systems. By replacing a visual signal analysis with an automatic one, the physician's task is facilitated and rendered more efficient and reliable. Automatic EEG analysis can also be useful in neurophysiological studies.

When an evoked potential (EP) is to be automatically analyzed, the EEG signal must be properly processed. In fact, the EP signal is to be extracted from the global EEG signal, isolating it from potentials which are not related to the sent stimulus. These potentials and the background brain activity are considered to be undesirable noise. An outstanding characteristic of EPs is the very unfavourable signal to noise ratio (SNR); in fact, the background EEG activity is more powerful than the EP itself (by one order of magnitude or more). In most cases, noise is reduced by performing a synchronized average of several successive recordings of the EEG signal, under the hypotheses that noise and EP are uncorrelated, noise is additive and phase-uncorrelated with stimulus time. These hypotheses can be verified at an interval of a few seconds, during which background EEG (i.e. additive noise) can be considered as a stationary, zero-mean process. This is not yet true for the duration of hundreds of averaged sweeps.

The averaging technique has the advantage that its implementation is very simple, but it levels off differences in latency and amplitude and requires a large number of recordings.

Another technique used to improve SNR is filtering. Using filtering fewer recordings are necessary, but a properly cut frequency for the filter must be chosen.

However, these methods are not appropriate when the responses to the repeated stimuli are variable, depending on the attentional state of the subject and on the "saturation" of neural cells to the stimulus.

3. THE AUTOREGRESSIVE MODEL

In order to overcome the limits of traditional techniques, we have studied a method for automatically processing and analyzing EP signals, that is more sensitive than the simple averaging or bandpass filtering techniques.

The method we have considered is based on the AutoRegressive model with exogenous input (ARX) proposed in [CER87, LIB89], that makes it possible to consider the EEG signal as the superimposition of a noise component (background activity of the Central Nervous System) and a signal correlated with the stimulus (the EP). We will show that by properly modifying this method the EP can be extracted by using a *single* EEG sweep. In this way, variations in different successive recordings can also be detected and used in diagnosis.

3.1 The ARX model

The ARX model is described in its most general form in the discrete time domain, by the equation:

$$y_r(k) = - \sum_{i=1}^n a_{ri} y_r(k-i) + \sum_{j=d}^{m+d-1} b_{rj} u(k-j) + e_r(k) \quad (1)$$

where $y_r(k)$ is the k -th sample of output signal relevant to the r -th sweep; $k=1$ corresponds to the instant of stimulus S_1 ; $u(k)$ is the k -th sample of the reference input signal; the first summation is an autoregressive component of order n that weights the previous n samples of output signal $y_r(k)$; the second summation is a moving average of m samples of the signal $u(k)$; $e_r(k)$ is white noise. The relative delay between the input reference signal $u(k)$ and the output recorded noisy signal $y_r(k)$ is taken into account by the parameter d . When $d > 0$, there is delay of the output with respect to the input, while a value $d < 0$ means a delay of the input with respect to the output.

In the z -transform domain, equation (1) is transformed into:

$$A_r(z)Y_r(z) = B_r(z)U(z) + E_r(z) \quad (2)$$

where $Y_r(z)$, $U(z)$ and $E_r(z)$ are the z -transforms of $y_r(k)$, $u(k)$, $e_r(k)$.

$A_r(z)$ is defined as follows:

$$A_r(z) = 1 + \sum_{i=1}^n a_{ri} z^{-i}$$

and

$$B_r(z) = z^{-d} \sum_{j=0}^{m-1} b_{rj} z^{-j}$$

Expressions (1) and (2) can be represented by the block diagram shown in Fig. 1 describing the system with its transfer functions.

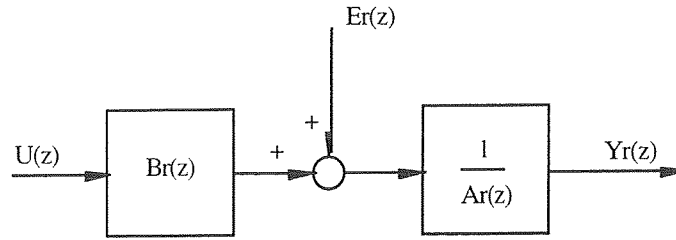


Fig. 1: The ARX model in the z-transform domain.

Given the temporal series $y_r(k)$ and $u(k)$, the first step in the processing procedure is to identify the values of the coefficients a_{ri} ($i=1, \dots, n$) and b_{rj} ($j=d, \dots, m+d-1$) which characterize the model for the r -th sweep. Because of the linear structure of the ARX model, a_{ri} and b_{rj} can be evaluated by a simple least squares approach, minimizing the variance of the prediction error $e_r(k)$:

$$Q_r = \sum_{k=1}^N [e_r(k)]^2 \quad (3)$$

where N is the number of samples of $y_r(k)$, $u(k)$, and $e_r(k)$. The term $e_r(k)$ can be interpreted as the prediction error of the realization of the model we are analyzing. The hypothesized ARX model requires that the process $e_r(k)$ is a white noise process. The whiteness of the residual $e_r(k)$ can be checked by using the Anderson test, with a confidence of 95% [BOX76]. A not-significant whiteness test makes the identified values meaningless.

The Anderson test consists of computing the coefficients of the normalized autocorrelation by means of the formula:

$$\rho_r(\tau) = \frac{\sum_{i=0}^N e_r(i)e_r(i-\tau)}{\sum_{i=0}^N e_r^2(i)} \quad \tau = 0, \dots, N-1$$

and then of verifying that the coefficients belong to the interval $[-\lambda/\sqrt{N}, \lambda/\sqrt{N}]$ with a confidence factor $\alpha=0.95$ and with λ obtained from:

$$\frac{1}{\sqrt{2\pi}} \int_{-\lambda}^{\lambda} \exp(-x^2/2) dx = \alpha \sqrt{2\pi}$$

If the number of coefficients whose value is outside of the band is greater than $\alpha\%$, then the hypothesis of whiteness of noise $e_r(k)$ is not verified.

The identification algorithm could in principle be applied to each non-negative integer value of n and m , and to each integer value of d , independently. The number of coefficients $n^*=n+m$ has to be large enough to take into account as much information as necessary on the correlation between processes $y_r(k)$ and $u(k)$, but at the same time it must be the as small as possible as it defines the order of the model. An a posteriori synthetic evaluation of these values is possible with the function AIC (Akaike Information Criterion, [BOX76]), which is a compromise between these two opposing requisites. The function AIC is defined as:

$$AIC(n,m,Q_r) = \ln(Q_r) + 2n^*/N \quad (4)$$

This depends on the delay d between y_r and u . The minimum value assumed by AIC gives corresponding optimal values for m , n , d .

The use of the ARX model in processing EEG signals is based on the assumption that recorded electrical activity is the sum of the EP and the background EEG [PER69, REG72]. The background EEG is described as an AutoRegressive process driven by white noise [CER85, GER70, ZET69], while the estimated EP is a deterministic signal obtained from the reference average $u(k)$ through a linear filtering.

On the basis of the above considerations, the block diagram of Figure 2 can be drawn. In terms of input-output transfer functions this is equivalent to the model of Figure 1. However, in this case, the model belongs to the ARX class, and the parameters of each sweep can be estimated by means of the procedure described above.

A single-sweep EP is synthetically described by the set of $m+n$ parameters a_{ri} and b_{rj} ; its waveform in the time domain is obtained by

filtering the reference $u(k)$ with a transfer function $B_r(z)/A_r(z)$. This procedure implies the calculation of the optimal order for each recorded sweep, by means of the Akaike Criterion (Eq. (4)). This operation can be very time-consuming as it consists of the iteration of the identification procedure for all the values n, m, d . These values vary independently within a limited range in order to ensure the termination of the identification algorithm [CER87, CER88]. The reduction of this range will speed up the computation process, which is essential for on-line clinical monitoring. On the other hand, the identification with the selected order must take into account the whiteness of the prediction error, which is a necessary condition when formalizing the ARX model. Moreover, identification with an order close to the optimal is desirable in order to extract the maximum information with a minimum of parameters. A second level of compromise is thus involved, so as to satisfy the necessity to select a fixed order of n, m, d which is appropriate for all the sweeps in the protocol.

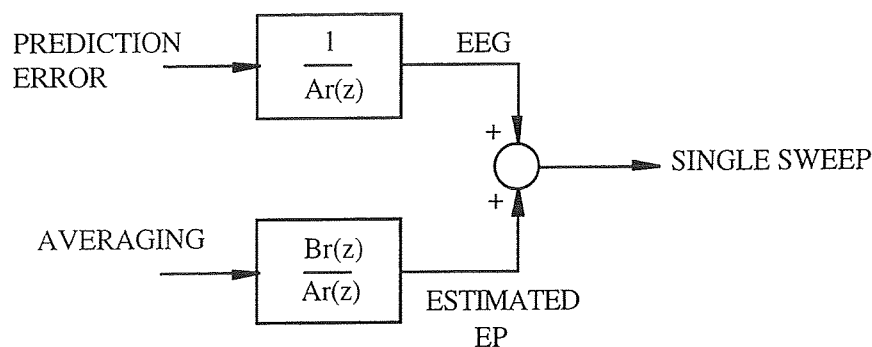


Fig.2 Implementation of the ARX model obtained as a sum of two signals.

The choice of the reference signal $u(k)$ is also crucial. The selection of the total average of all the recorded sweeps, suggested by the traditional approach with synchronized averaging, has been shown to be satisfactory [CER87]. The construction of the reference signal as a partial average of a reduced number of sweeps has been described in [LIB89]; its advantage is that it speeds up the initialization procedure during on-line monitoring. It must be noted, however, that more than a single sweep is used in processing the signal. Our task is the reduction of the total analysis time by using just one sweep for each trial.

3.2 Data analysis and implementation of ARX model

We have processed data provided by the Neurological Clinic of Careggi Hospital, Florence, Italy. They are CNV response signals, recorded in a healthy male subject, 32 years old. The auditory warning stimulus S1 was a click lasting 200 μ sec; the imperative signal S2 was a visual stimulus, produced 2 seconds after S1. It required the subject to push a button. Fifteen electrodes were located on the scalp according with system 10/20. The EEG signal was recorded for 400 sec after S1 and was filtered between 0.03 and 30 Hz, sampled with a sampling rate 400 Hz and A/D converted. Each sample represents the signal amplitude expressed in μ V; it can vary in the range $-50\mu\text{V} \div 50\mu\text{V}$; it is coded by an integer number. For each sweep, we have considered the trace derived from the electrode Cz, located in the region in which the answer to the auditory stimulus is most evident. In this trace, we have considered only $N=100$ samples post-stimulus. This corresponds to a delay of 250 msec after the stimulus.

At first we processed data by applying the method proposed in [LIB89]. The reference signal was considered zero before stimulus, as EP is absent before then. Whiteness of noise was verified by means of Anderson test with a confidence factor 95%. To detect the optimum order of parameters, we chose the following ranges:

$$2 \leq n \leq 12 \qquad 2 \leq m \leq 12 \qquad -10 \leq d \leq 10$$

By developing computation, we saw that for m and n close to the minimum of their range and for $d > 0$, noise was not white (the Anderson test was not satisfied). An overestimate of n did not significantly affect the filtering, while values of m and d were crucial, as was to be expected, since m and n characterize the position of the moving average over the reference signal. They did not affect the whiteness of noise, but could produce a distortion in the amplitude and latency of the EP. Optimum order for all sweeps was obtained for small m and n and $d < 0$ (strictly). In particular, we found the following values:

$$n=9 \qquad m=4 \qquad d=-9$$

We also verified that the resulting filter was stable by studying its impulsive response in the time domain; we checked that the output signals to impulsive input signals were absolutely summable.

4. THE SPATIAL ARX MODEL

As we have already noted, the most critical point of the ARX model described in the previous section is the choice of the reference signal, which is an average obtained from several previous sweeps. This also means that the method proposed in [LIB89] does not work for a single sweep, but only with a reduced number of sweeps. The use of a single sweep would be of particular interest since it could allow a faster processing of the EEG and a smaller storage request. Moreover, some EPs can last only for a few sweeps, not allowing the temporal averaged reference signal to be obtained. In addition, if the trial can only last for one sweep, both "long-time variability" effects, due to different psychological conditions of the patient (attentional level, tiredness, etc.) and "short-time variability" effects, caused by stochastic variability in the neural population and by neural cells becoming accustomed to repeated stimuli, can be avoided.

We thus studied and developed an extension of the ARX model, which works with just a single sweep. The idea is based on the fact that electrodes located in a scalp region surrounding the Cz location record signals with similar shapes, such as the shapes of signals of successive sweeps. This has suggested using a "spatial" average instead of the classical temporal average as the reference signal (SpatialARX). A spatial average is obtained from signals detected during a single sweep by a set of closed electrodes, located in the encephalic region which is most stressed by the sent stimulus. This procedure is clinically equivalent to that proposed in [LIB89]. It receives all information available in a single sweep time and allows the recording session and the diagnosis times to be reduced, with all the advantages described above.

4.1 Data analysis and implementation in the Spatial ARX model

The procedure we followed when recording and analyzing signals with SARX model is quite similar to that followed with the ARX model. Signals recorded by the electrode relevant to the 11th track and by electrodes surrounding it, located on a grid 3x3, were considered. Again in this case, only 100 samples post-stimulus were considered. The reference signal was not considered outside the spatial interval covered by 3x3 electrodes. The signals collected were processed as for the ARX

model: coefficients a_{ri} and b_{rj} were computed by the least squares method; the Anderson test was applied to noise to verify its whiteness with a confidence factor 95%; Akaike criterion was applied to define the optimum value for m , n and d ; the stability of the model was tested.

To detect the optimum order of parameters, we chose the following ranges:

$$2 \leq n \leq 12 \qquad 2 \leq m \leq 12 \qquad -10 \leq d \leq 10$$

As a result, we found the following values:

$$n=8 \qquad m=5 \qquad d=-7$$

5. EXPERIMENTAL RESULTS

EEG signals recorded after sending an auditory stimulus, as described in the previous sections, were processed by the ARX algorithm using a temporal average and a spatial average.

For the ARX model, we used signals detected by electrode Cz, during 8 sweeps; for the SARX, model we used signals detected by electrode Cz and by 9 surrounding electrodes, in a 3x3 matrix. In both cases, optimal values of m, n and d were computed by AIC and then used. In order to verify our approach, we computed a correlation coefficient c_{rs} between the r-th evoked response, estimated by means of temporal averaging, and the s-th evoked response, estimated by means of spatial averaging, in accordance with the following formula:

$$c_{rs} = \frac{\sum_{i=1}^N (y_{ri} - \bar{y}_r)(y_{si} - \bar{y}_s)}{\sqrt{\sum_{i=1}^N (y_{ri} - \bar{y}_r)^2 \sum_{i=1}^N (y_{si} - \bar{y}_s)^2}}$$

where y_{ri} and y_{si} are samples of each signal obtained, via temporal and spatial averaging, respectively; \bar{y}_r and \bar{y}_s are their main values and N is the total number of samples.

The results obtained are showed in Table 1, whose elements are the correlation coefficients c_{rs} (r-th row and s-th column). As an example, let us consider data relevant to the fourth of the eight recorded responses. They are shown in Figures 3 and 4 for the cases of temporal and spatial averaging, respectively. In Fig. 3a the experimental EP is shown; Fig. 3b depicts the estimated EP obtained for r=4 using the temporal average and the estimated noise $e_4(k)$ is shown in Fig. 3c. Analogously, Fig.4a shows the same experimental EP of Fig. 3a; in Fig.4b the estimated EP obtained for s=4 using spatial averaging is shown and in Fig.4c the estimated noise with the spatial average method is displayed. From the table, we can see that the correlation coefficient relevant to these signals was $c_{44}=0.93$. The values on the main diagonal are a sort of resemblance coefficient between the shapes of EPs detected by the two algorithms, hence the fact that they are generally close to 1 means that there is a good agreement between results obtained with the two methods.

$r \backslash s$	1	2	3	4	5	6	7	8
1	0.90	0.86	0.94	0.93	0.47	0.88	0.84	0.92
2	0.81	0.94	0.86	0.83	0.64	0.91	0.92	0.82
3	0.87	0.86	0.96	0.87	0.60	0.86	0.87	0.89
4	0.90	0.86	0.94	0.93	0.47	0.88	0.84	0.92
5	0.60	0.82	0.61	0.60	0.70	0.78	0.87	0.67
6	0.86	0.93	0.91	0.87	0.64	0.93	0.93	0.88
7	0.78	0.92	0.86	0.80	0.73	0.89	0.96	0.83
8	0.89	0.83	0.91	0.93	0.40	0.86	0.80	0.92

Table 1: Correlation coefficients between the estimated EP obtained using the ARX and the SARX methods.

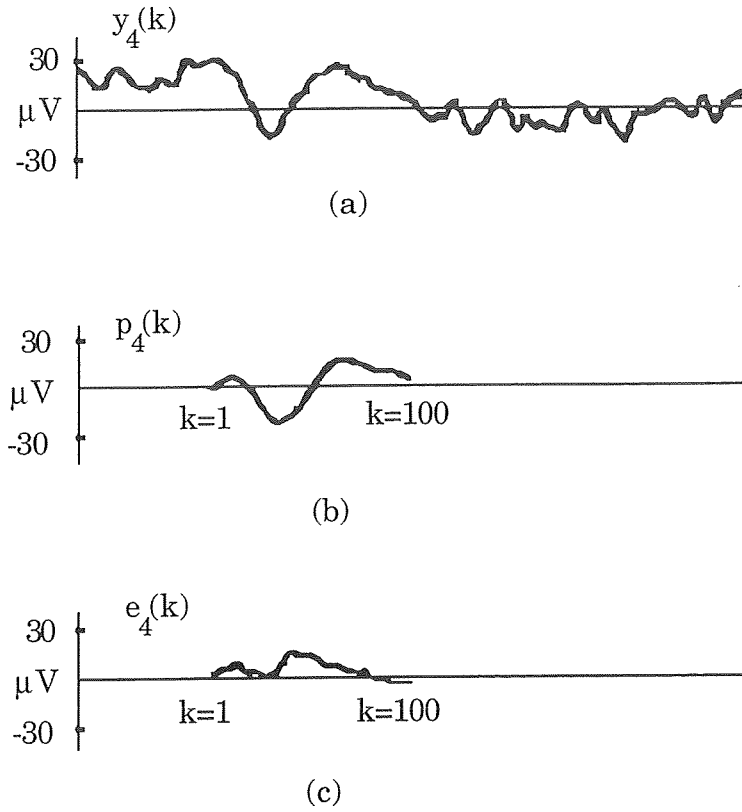


Fig.3: Temporal averaging. (a): the experimental EP; (b): the estimated EP obtained for $r=4$; (c): the estimated noise $e_4(k)$.

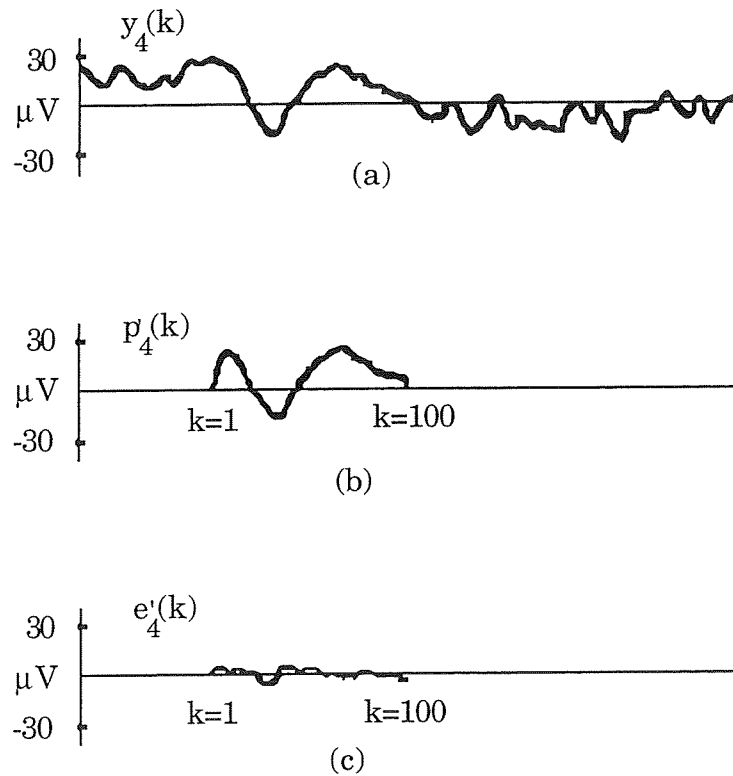


Fig.4: Spatial averaging. (a): the same experimental EP of Fig. 3a; (b): the estimated EP obtained for $s=4$; (c): estimated noise.

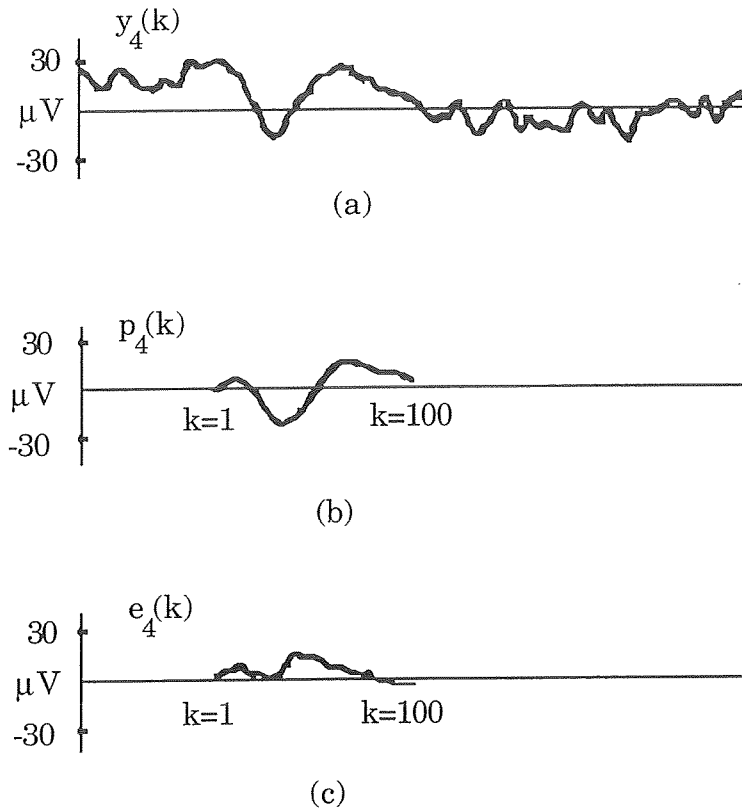


Fig.3: Temporal averaging. (a): the experimental EP; (b): the estimated EP obtained for $r=4$; (c): the estimated noise $e_4(k)$.

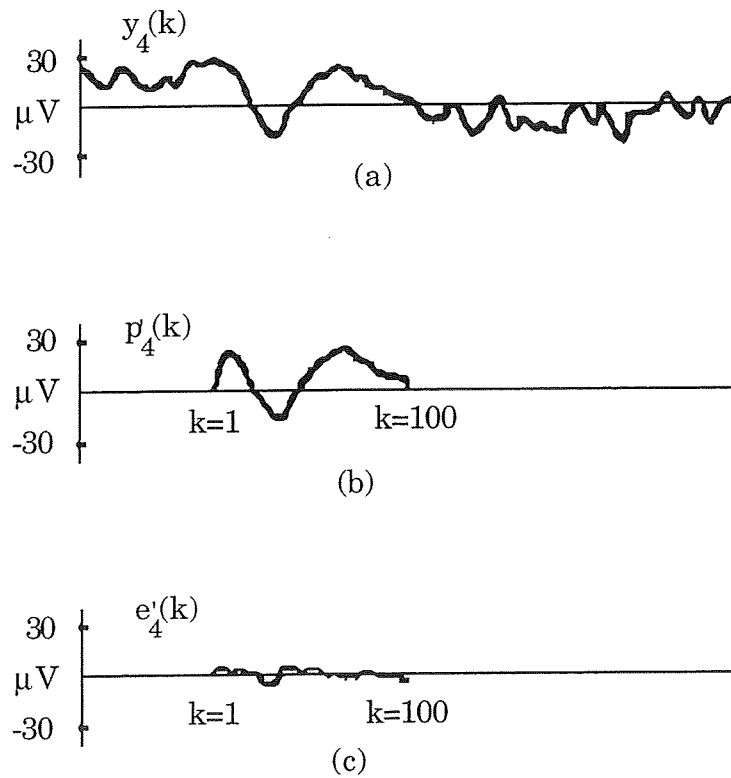


Fig.4: Spatial averaging. (a): the same experimental EP of Fig. 3a; (b): the estimated EP obtained for $s=4$; (c): estimated noise.

6. CONCLUSIONS AND FUTURE WORK

As Table 1 shows, the results obtained with the modified ARX seem to confirm our basic idea and are encouraging. The agreement between the results obtained suggests that the autoregressive model is able to predict variations in single responses in a satisfactory measure.

However, it must be noted that signals have been recorded in optimal conditions, i.e. with a good SNR. Our method should be tested on signals with a lower SNR and affected by artefacts.

Moreover, the method should be tested with a reference signal obtained from a larger number of recordings. So far, we have been unable to do this, as we have too few data at our disposal.

Another interesting experiment could be performed by applying our method to EPs caused by several contemporary stimuli.

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