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Dynamic Time Warping in the study of ERPs in dyslexic children

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Abstract—**Aim of this paper is to compute a normal ERP pattern (*template*) and to quantify the morphological characteristics of ERPs. ERPs were recorded from normal and dyslexic children in a passive and in an active condition. Dynamic Time Warping (DTW) was used to align the averaged ERPs of normal subjects. After the computation of the templates, individual averaged ERPs were aligned with the corresponding template, in order to automates the identification of the relevant ERPs components. The latencies of these components in normal and dyslexic subjects were compared in the two different conditions. ERPs components of dyslexic children were always delayed in respect to normal children. Statistically significant latency differences were noticed both in the short-latency waves, related to attention mechanisms, and in the long-latency waves, presumably related to memory processes. P1 latency in T4 differed in the two groups of children in both tasks, with p<0.05. Morphological differences between the ERPs of normal and dyslexic children were also noticed in the right hemisphere: N2 latency in T4 differed in the two groups of children with p<0.05. This result suggests that dyslexia is associated with more general disruptions of the cerebral functions than that confined to the classical linguistic areas.**

Keywords—**Dynamic Time Warping, ERPs, dyslexia, reading-related potentials.**

I. INTRODUCTION

Developmental dyslexia is a neurological disorder characterized primarily by reading difficulties despite average intelligence, adequate education and normal sensory acuity. The aetiology of this condition is still unknown: the most recent theories hypothesize a genetic disruption of the cerebral structure, that would produce compromised phonological awareness and visual/auditory perception [1]. In order to investigate the reading processes, event-related potentials (ERPs) were recorded in normal children and in children with developmental dyslexia. This approach is particularly efficacious for our purposes because it allows to investigate the functional aspects of cerebral activities with an high temporal resolution, in a non-invasive way. Comparing ERPs from different subjects is difficult for the high inter-individual variability of the morphology: dealing with children performing cognitive tasks this variability greatly increases. As a consequence, it is difficult to define a normal "pattern". Usually, a grand-average is evaluated from a group of normal subjects, but this is heavily affected by inter-individual variability. In this work we propose an approach based on Dynamic Time Warping (DTW) technique for the automatic alignment of the waves and quantification of the morphological characteristics of ERPs. The method allows the calculation of a reliable template for normal subjects, which can be compared with pathological signals.

II. METHODOLOGY

Dynamic Time Warping (DTW) is a non-linear alignment algorithm that reduces the temporal differences between signals with similar morphologies through local compressions and extensions of their temporal axes [2,3]. The DTW procedure consists in performing two different steps on paired signals: i) calculation of a Warping Function (WF) representing the best alignment between the signals; ii) computation of a new waveform (template) by averaging the original signals according to the WF. Given two signals

$$x = \{x_i \quad 1 \le i \le I\} \qquad (1)$$
$$y = \{y_j \quad 1 \le j \le J\}$$

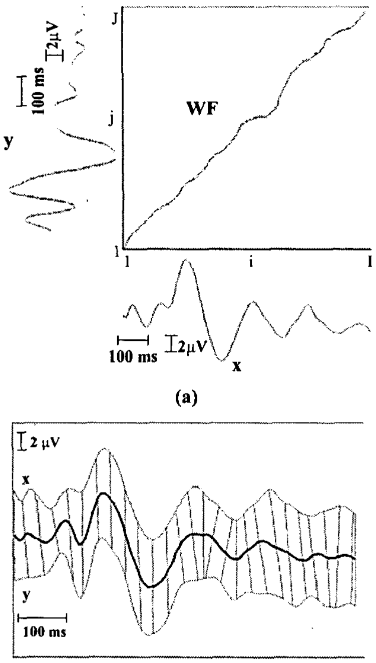

Fig. 1. a) Plot of the Warping Function computed on the sampled signals x and y. b) Thin lines represent the original signals x (top) and y (bottom). Thin segments represent the temporal correspondence between morphologically similar samples of the two signals. Thick line represents the template resulting from the alignment of x and y

with the same sampling rate, it is possible to represent the temporal correspondence between their fiduciary points through the function:

$$\mathbf{WF} = \{WF(k) = (i(k), j(k)) \quad 1 \le k \le K\}. \qquad (2)$$

The WF can be graphically represented as in figure 1a.

The WF has the boundary limitations: WF(1)=(1,1) and WF(K)=(I,J). Furthermore, it has to be continuous and monotonic not decreasing. In order to prevent excessive adjustment of the time axes during alignment, the WF has to be confined in the region around the main diagonal defined by

$$|i(k) - j(k)| \le r. \qquad (3)$$

In the present work, the value of r was fixed to 8 samples corresponding to 32 ms (see experimental protocol). In order to avoid that alignment can be confounded by the noise superimposed to the useful signal, a slope constraint condition has to be imposed to the WF. This condition can be expressed by the following parameter:

$$p = n / m \qquad (4)$$

where n represents the number of diagonal segments and m the number of horizontal or vertical segments that the WF can consecutively contain. This constraint prevents that, after m consecutive horizontal or vertical segments, the WF steps further in the same direction without making at least n consecutive diagonal segments. In the present work, the value of p was fixed to 1. In order to compute the WF, a measure of the morphological distance between the samples of the signals has to be defined. We used the dissimilarity function described by the following equation:

$$d(k) = |x_n(i(k)) - y_n(j(k))| + |x'_n(i(k)) - y'_n(j(k))| \quad (5)$$

with n indicating normalization. The dissimilarity function was computed at every point of the warping plane, satisfying the previously imposed constraints. The WF is constructed by minimizing the cost of alignment, that is a weighted sum of the values of d(k). Applying the Dynamic Programming (DP) equations:

$$g(k) = \min_{k-1}[g(k-1) + d(k)s(k)] \qquad (6)$$

with the initial condition:

$$g(W(1)) = g(1,1) = d(1,1)s(1) \qquad (7)$$

it is possible to obtain a matrix $\underset{(I,J)}{\mathbf{G}} = [g(k)]$. The generic element g(k) measures the minimum cost to reach the point (i(k),j(k)) from (1,1). The best alignment is obtained as the path in matrix **G** with the minimum cost reaching the point (I,J) from the point (1,1). The weights s(k) determine if alignment has to privileges the compression or the extension of the temporal axis of one of the signals. In the present work all the signals were supposed to convey the same information and then a symmetric alignment was performed. In this condition s(k) equals 2 if the segment between WF(k-1) and WF(k) is diagonal; otherwise s(k) equals 1. The template is obtained by mixing the samples of the two signals according to the WF [3]. An example of alignment and template computation is shown in figure 1b.

The computation of the template on more than two signals is realized by iteratively applying the method described above to paired signals following a binary tree structure. After the computation of a template for a set of signals, the alignment of the template with each of the original signals produces a temporal correspondence between the samples of the template and the signals. As a consequence, it is possible to identify on the original signals the latency of specific, physiologically significant waves marked in the template. This approach realizes the automatic quantification of the ERPs morphology. The temporal window involved in alignment was set to 0-700 ms. This window is large enough to contain the relevant components of the ERPs we were interested in.

III. EXPERIMENTAL PROTOCOL

8 normal children (mean age 8.75 ± 0.26 years) and 8 children with developmental dyslexia (mean age 8.47 ± 0.41 years) underwent the experiment. The stimuli consisted in the presentation of Italian alphabetic capital and small letters and were presented 4 times in the same random order for all subjects. All subjects performed two tasks. In the first task, called *letter presentation,* subjects were called to passively watch at letters without making any effort in reading or articulating silently them. In the second task, called *letter recognition externally-paced,* subjects were called to reading aloud the letters [4]. The use of single isolated letters rather than words was decided to avoid that semantic inferences from the context might influence the reading processes of dyslexic children. The first task can be considered as a passive condition; the second task an active condition. EEG was recorded from Fz, Cz, Pz, Oz, C4, C3, T4, T3, P4, P3 referred to linked mastoid. The EOG was bipolarly recorded using 2 electrodes diagonally placed over and below the right eye. EEG and EOG recordings were bandpass filtered between 0.02 - 30 Hz. The EEG and EOG signals were sampled at 250 Hz, with 4 seconds analysis time, 2 s pre- and 2 s post-stimulus. In order to improve the SNR of ERPs, we reduced the ocular artefacts before computing averages using Principal Component Analysis as described in [5]

IV. RESULTS

The method was separately applied to the ERPs recorded from normal and dyslexic children in two different conditions. As an example, the superimposition of the normal and pathological templates recorded during *letter presentation* task is shown in figure 2.

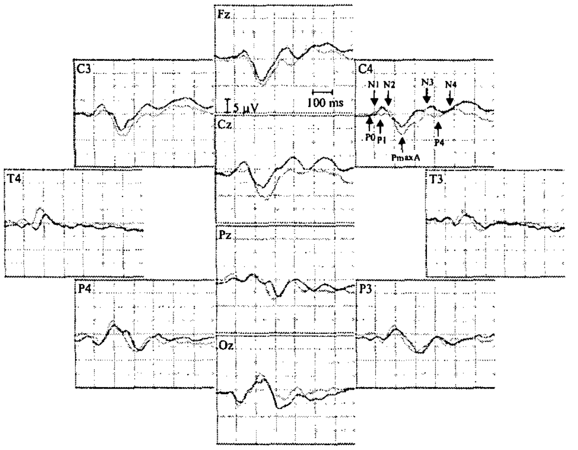

Fig. 2. Superimposition of the ERP templates of normal children (thin lines) and dyslexic children (thick lines) for all the considered EEG channels. As an example in C4 the relevant components are indicated by arrows.

Figure 3 shows the relevant components we considered useful for the statistical analysis of ERPs morphology.

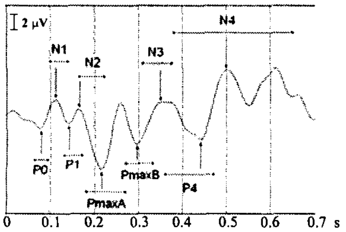

Fig. 3. Relevant ERPs components and temporal intervals in which they are generally found. This trace is a real ERP recorded from channel C4 in a normal subject.

The exact functional meaning of the ERPs components is not precisely known: however, it is possible to identify in the ERPs three periods according to their temporal position [6,7]. The short-latency components (P0, N1, P1) belong to the pre-lexical period: they mainly result from the sensorial processing of stimuli. P1 is particularly evident in Oz, because it is related to the primary visual cortex activation in correspondence to the presentation of the stimulus. The middle-latency components (N2, PmaxA, PmaxB, N3) belong to the pre-lexical period: they are mainly concerned with the stimulus categorization. The long-latency components (P4, P600a, N4) belong to the post-lexical period: they presumably reflect long-term semantic memory processes. By convention, the same positive wave is called P600a in the parietal and occipital areas (Pz, Oz, P4, P3) and P4 in the other areas.

The relevant components of the templates obtained from the control group and the group with developmental dyslexia in the two conditions were identified and marked. Then, all the individual ERPs were aligned with the adequate template and the temporal correspondence between the relevant samples of the template and of the individual ERPs was considered. The measures resulting from this approach were verified and eventually manually corrected. A two-sided t-test analysis was performed to compare the latencies of the relevant ERPs components in the two groups of children performing the same task. The results of this analysis are shown in tables 3 and 4: the mean and standard deviation values of the latencies of the relevant components are indicated for the control group and the group with dyslexia. Only the comparisons with statistical significance $p<0.05$ are reported. Considering the passive task, the latency difference of N4 component in Pz greatly differs ($p<0.01$) between the two groups of subjects: it equals 494.9±23.1 ms in normal children and 548±31.7 ms in dyslexic children. The latency of N1 and N4 components in C3 is significantly different ($p<0.05$) in the two subject categories: N1 latency is 99.2±16.3 ms in normal and 135.4±22 ms in dyslexic children; N4 latency is 505±28 ms in normal and 547±36.4 ms in dyslexic children. Considering the active task, the greater morphological difference ($p<0.01$) between normal and dyslexic children is relative to P4 component in Fz: latency is 390.7±11.18 ms in normal and 429.6±23.6 ms in dyslexic children.

Table 2: Mean and standard deviation values of the relevant ERPs components latency (ms) in the EEG channels, in normal (N) and dyslexic (D) children during *letter presentation* task. Normal characters indicate that the comparison between the two groups is significant with $p<0.05$; underlined characters indicate $p<0.01$.

		P0	N1	P1	N2	N3	P4	N4			N1	N3	N4	P600a
Fz	N		105±12,4				396,8±23,7		Cz	N	100±14,4			
	D		137,1±19,6				422,5±17,2			D	136±23,6			
C4	N	72,7±9,9	102,9±10,8		167,5±5,8	356±15,8	409,6±26,3	500±28,4	Pz	N	88,6±9,1		494,9±23,1	448,7±17,1
	D	107±28,5	129,7±22,6		190±19,2	378,3±19,7	454,3±17,7	540,6±22,4		D	125,1±29,4		548±31,7	492,6±32,4
C3	N		99,2±16,3					505±28	Oz	N		397,1±26,9		
	D		135,4±22					547±36,4		D		430±28,2		
T4	N	61±8,3		135,3±6,9	181,5±11,1				P4	N		382,3±25,9	500±17,3	444,7±20,8
	D	95,5±26,2		153,3±12,3	210,7±9,4					D		418,5±22,8	545,7±20,3	496±33
T3	N				192±12,5	349,1±16,6			P3	N		383,4±28,4		441,1±38,6
	D				216,7±18,1	389,3±25,9				D		410,9±15,3		498±36,5

Table 2: Mean and standard deviation values of the relevant ERPs components latency (ms) in the EEG channels, in normal (N) and dyslexic (D) children during *letter recognition externally-paced* task. Normal characters indicate that the comparison between the two groups is significant with p<0.05; underlined characters indicate p<0.01.

		N1	P1	N2	P4
Fz	N				390,7±11,8
	D				429,6±23,6
Oz	N		111±11,7		
	D		128,6±12,7		
T4	N		134,3±11,5	177,5±9,1	
	D		151±12,2	206,5±19,1	
T3	N	100±10,4		178,5±8,3	
	D	118±11,9		199,5±23,9	

V. DISCUSSION AND CONCLUSION

The latency of all the considered ERPs waves is always greater in children with developmental dyslexia than in normal children. This delay is present since pre-lexical period, thus suggesting that a simple delay in the low level processing of visual stimuli can disrupt all the high level processes subtended by reading learning and comprehension.

Comparison between normal and dyslexic children in the *letter presentation* condition. The mean latency difference is over 40 ms in the long-latency waves (P4, P600a, N4): this means that the slow and late components are altered in reading disabled children. As these components are related to memory, this confirms the reliability of the phonological theory about the origin of dyslexia [8]. The latency difference was statistically significant also for the waves belonging to the pre-lexical period (P0, N1). These components precede the arrival of the visual stimulus in the primary visual cortex and then are presumably related to attention mechanisms. The subject is consciously participating a reading-related task: this condition probably elicit in normal children some attention and concentration mechanisms to be active. In children with developmental dyslexia this mechanism seems disrupted. The most significant morphological differences in the two categories of subjects occurred in correspondence to the parietal, temporal and central regions of the brain (recording channels Pz, P4, P3, T4, T3, C4, C3). Left hemisphere is associated with linguistic processing; the finding of abnormalities in the right hemisphere in language-impaired subjects supports the hypothesis of dyslexia as a spread disorder, not limited to the classical brain area normally involved in linguistic abilities.

Comparison between normal and dyslexic children in the *letter recognition externally-paced* condition. In this condition, the latency differences between normal and dyslexic children are less significant than in the passive condition. ERPs recorded during active tasks have a smaller SNR that during passive ones, because of the greater number of artefacts deriving from gross body movements. Morphology of ERPs is altered by these artefacts and by the small number of averaged trials. Temporal areas (T4, T3) register the greatest morphological differences between the two groups of subjects. The statistically significant latency differences between normal and dyslexic subjects are evident in the short- and long-latency components. This result confirms that dyslexia is a pathology in which not only the reading processes, but also more general functions, at different time scales, are compromised.

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