TECHNICAL NOTES

A METHOD FOR AUTO- AND CROSS-RELATION ANALYSIS OF THE EEG

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INTRODUCTION

Various analysis methods have been introduced in electroencephalography for studying rhythmic phenomena and for studying mutual relations of phenomena occurring in different channels. (For literature see Storm van Leeuwen and Magnus 1961). By most of these analysis methods some form of extraction of information is carried out, so that certain aspects are presented more clearly than in the original EEG and others are lost. The data obtained with the various analysis methods may overlap, but are not the same. In the present communication a method is described for the study of rhythmic phenomena and mutual relations between phenomena. The method is called auto- and cross-relation. A somewhat similar method has been described by Sato *et al.* (1962a, b), who carried out formal calculations of auto- and cross-relations, called by them "simplified method for auto- and cross-correlation". (As will be discussed later the present authors are of the opinion that relation analysis is not a correlation method.) This formal procedure is time consuming and, therefore, usually the relations of a relatively small number of successive waves are calculated. Thus, possible relations of the signals are not represented reliably. Automation of the method, therefore, is preferable. In the following a method will be described for automatic auto- and cross-relation analysis developed in this Institute. (See also Storm van Leeuwen *et al.* 1963.)

METHOD

In principle the cross-relations of two signals are determined in the following way. At comparable time points of one of the signals—referred to as the "reference signal"—pulses are generated. (Fig. 1, upper and middle traces).

The pulses serve as timing pulses for computing the relations with the second signal—the "analysed signal" (Fig. 1, lower trace). The computation may be carried out by means of an average response computer. The timing pulses are used for triggering the time base of the computer and the "analysed signal" is applied to its input. The outcome of the computation indicates the cross-relation of the two signals. The timing pulses may also be used for computing the relations with the same signal. In this case, auto-relations are obtained, as the analysed signal is the same as the "reference signal".

APPARATUS

As appears from the above the apparatus consists of two parts: the timing pulse generator and the average response computer.

Timing pulse generator

The timing pulses are obtained by a method which is a modification of the one described by Turton (1952) and by Bekkering and Storm van Leeuwen (1954), according to which, by means of a Lissajous figure the EEG is displayed circularly on the screen of a cathode ray tube. To this end the signal passes a network which effects a 90° phase difference between the signals at the horizontal and vertical deflection plates. A pulse is generated whenever the spot passes a photo-electric device, which is

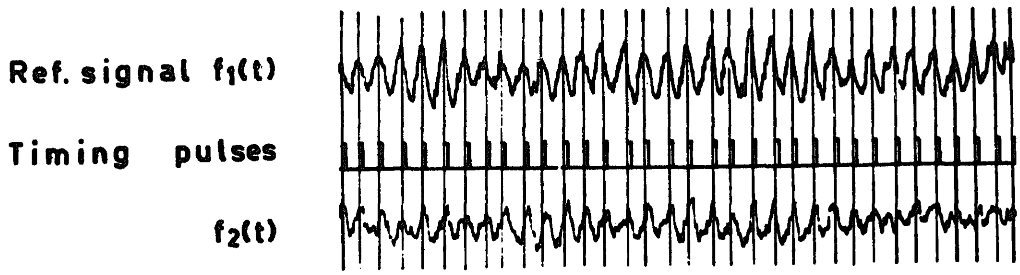

Fig. 1

Upper trace: Reference signal $f_1(t)$. Timing pulses are generated at the peaks of the waves. The timing pulses are drawn in the middle trace.
Lower trace: Analysed signal $f_2(t)$.

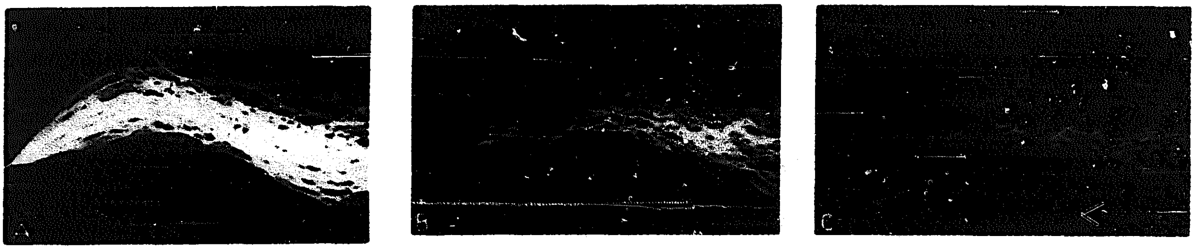

Fig. 2
Examples of auto- and cross-relation analyses obtained with Dawson's superimposition technique (49 samples). *A*: Auto-relation of the reference signal. *B*: Cross-relation of the reference signal and the analysed signal. The superimposition clearly indicates an interdependence of the two signals. *C*: Cross-relation of two signals which do not appear to be related.

placed on the screen of the cathode ray tube. The system works satisfactorily for rhythmic EEG phenomena such as alpha rhythms, even if these are mixed with a considerable amount of other activities, (see also Fig. 5). A diagram of the network is described separately (Kamp 1965).

Average response computer

Any device for obtaining average responses may be used. For instance, if Dawson's superimposition method is applied (Dawson 1947), auto- and cross-relations of alpha rhythms in man may be obtained, as shown in Fig. 2. In *A* an auto-relation of an alpha rhythm is demonstrated; in *B* it is shown that a cross-relation exists between two alpha rhythms; *C* is a cross-relation of two apparently independent alpha rhythms. With the superimposition method the timing pulses are used to trigger the time base of the CRO; the duration of the display is determined by the sweep time. This method is probably the simplest and cheapest way of obtaining an impression of auto- and cross-relations and their variations.

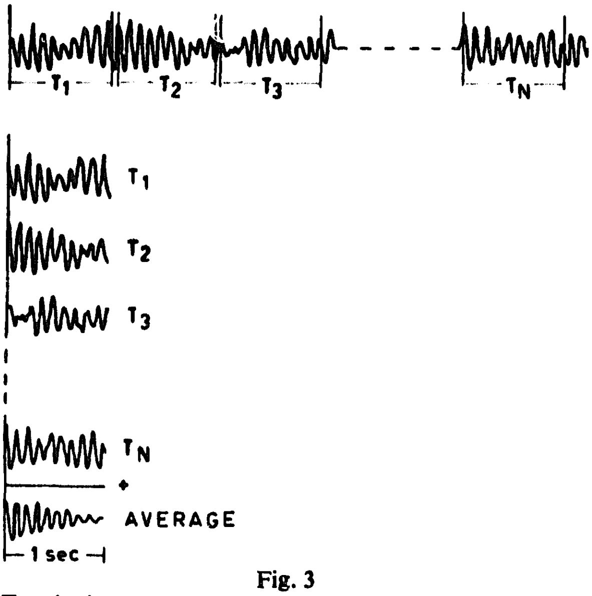

Fig. 3
To obtain an average auto-relation over a number of waves, the trace is split up in *N* parts, each lasting for time *T*. Each of the parts begins at a certain phase of the first wave, in this case at the peak. The duration *T* is determined by the sweep time of the average response computer, in this case 1 sec. The decay of the average gives an indication of the frequency and amplitude constancy of the signal.

An advantage of the superimposition method is the insight which may be obtained into the scatter around the most probable value. This information is lost if a relation is determined by means of averaging. Disadvantages of the superimposition method are that it is not very accurate and that time relations are not easily determined.

Because of these disadvantages the use of an average response computer is often preferable. In our investigations auto- and cross-relations have been determined by means of an analogue average response computer employing a barrier-grid storage tube according to Buller and Styles (1959) and Cooper and Warren (1961), and in some cases also by a Mnemotron Computer of Average Transients. The memory of the barrier-grid storage tube computer has a capacity of 144 inscriptions.

The time base is selected in accordance with the wave durations of the signal under study and—in case of auto-relations—of the number of waves to be analysed. Auto- and cross-relations obtained with this computer are shown in Fig. 4–7.

Auto-relations

By means of auto-relation studies an insight is obtained into the coherence of a rhythmic signal. To this end the time base of the averager is set at a duration long enough for inscribing a number of waves. The signal is thus split up into a number of parts, as shown in Fig. 3. Each of these parts begins at a certain phase of the first

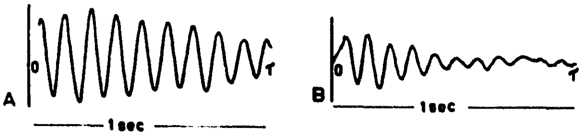

Fig. 4
Average auto-relations of occipital alpha rhythms in two human subjects (49 samples). *A*: Of a subject with a regular alpha rhythm. The decay is slow. *B*: Of a subject with a less regular alpha rhythm. The decay is faster, probably due to the wider frequency band of this subject's alpha rhythm.

wave, in this case at the peak. The average of these parts represents the auto-relation, the duration of which is equal to the sweep time. If the sweep time is 1 sec, if 144 inscriptions are used and if the analysed signal has a frequency of approximately 10 c/sec, a satisfactory estimate of the auto-relation is obtained. In Fig. 4 auto-relations are shown of alpha rhythms recorded from the right occipital areas in two normal subjects. Previous studies of the alpha rhythms in these subjects, carried out with continuous frequency analysis according to Bekkering *et al.* (1958), had shown that subject *A* had a regular, almost monorhythmic, alpha rhythm and that subject *B* had a more irregular alpha rhythm, clearly comprising more than one frequency. The auto-relation of the alpha rhythm of subject *A* shows a relatively slow decay of the amplitudes of the waves, indicating that the frequency spectrum of this alpha rhythm has a sharp peak (at 9.5 c/sec). The auto-relation of the alpha rhythm of subject *B* shows a much faster decay, which indicates that the alpha rhythm (or rhythms) in this subject has a wider frequency range or takes place in shorter coherent series than in subject *A*.

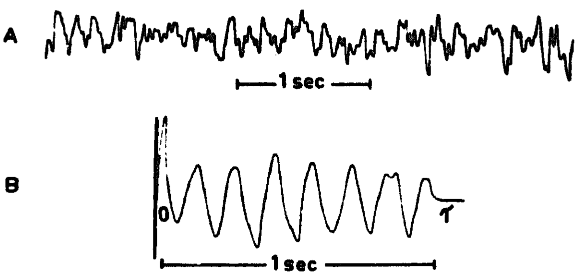

Fig. 5

A: Instrumentally composed signal, consisting of a sine wave at 7 c/sec and noise. Signal to noise ratio 1:2. *B*: Average auto-relation of the above. The sweep time *T* is 1 sec, 49 traces are averaged. The sine wave component of the complex signal clearly emerges.

The method may also be applied usefully if the amplitudes of the signals under study are smaller than the amplitudes of other activities. This is illustrated in Fig. 5, in which trace *A* depicts an instrumentally composed signal consisting of a sine wave at 7 c/sec and noise. If the signal-to-noise ratio is 1:2 the sine wave component is hardly apparent to visual inspection of the trace. Trace *B* shows the auto-relation of the complex signal; in this the sine wave component at 7 c/sec clearly emerges.

Cross-relations

By means of cross-relation studies an insight may be obtained into the mutual dependence of different activities and their time relations. This is demonstrated in Fig. 6, which depicts cross-relation analysis of alpha rhythms recorded from different chronically indwelling electrodes in a dog. By a simple delay line (tape recorder loop), a pre-selected time delay is introduced. This enables the relations to be determined also during a certain "negative" time and thus the accuracy of the time measurements is considerably improved. In Fig. 6, trace *a* represents the auto-relation of an alpha rhythm, the reference signal. To improve the measurement of the time relations part of the display is reproduced with an extended time axis in trace *b*, by increasing the sweep velocity of the computer time base. The traces *c*–*i* represent the cross-relations of the reference signal to the alpha rhythms recorded from other electrodes. The vertical line through the traces

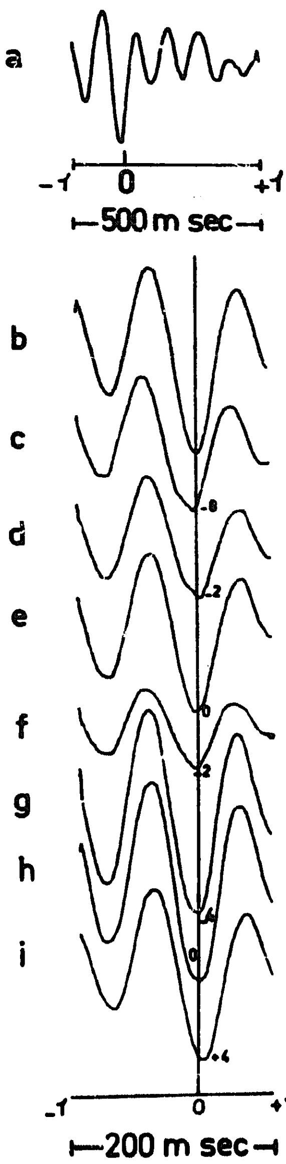

Fig. 6

Auto- and cross-relations of alpha rhythms recorded from electrodes placed 2 mm apart on occipital cortex of dog (100 samples). *a*: Auto-relation of reference signal. *b*: Same auto-relation with extended time axis. *c*–*i*: Cross-relations showing small time differences at some of the electrodes (negative time introduced by means of a delay line).

indicates zero time. Small time differences are observed, which repeated analyses demonstrate to be consistent.

Frequency selection method

If a phenomenon is investigated which takes place randomly in bursts, and if other activities take place, some of the timing pulses may be generated by these latter activities. Thus, some of the inscriptions in the memory of the average response computer do not relate to the phenomenon under study and the resulting auto- or cross-relation is distorted. This difficulty cannot always be overcome by increasing the number of inscriptions, as the disturbing signal may go on. In this case the signal-to-noise ratio may not be improved by the increased number of samples. This eventuality may be encountered, for instance, during alpha rhythm investigations if the subject every now and again falls asleep. In this case the auto- and cross-relations of the alpha rhythms may be distorted by the occurrence of activities at low frequencies. The difficulty may be overcome by ensuring that a sufficient number of timing pulses is generated by alpha rhythms and not by the other activities. This may be effectuated by introducing a system which allows the averager to work only on certain conditions, for instance, if rhythmic activities at 8–15 c/sec are present while 0.5–6 c/sec activities are not. This system may be regarded as a simple form of pattern recognition. It has been achieved by the use of two frequency selective filters, one of 8–15 c/sec and the other of 0.5–6 c/sec, which influence a gate through which the timing pulses pass. If the rectified output of the 8–15 c/sec filter surpasses a certain level the gate is opened and the timing pulses may pass through. However, if the voltage of the rectified output of the 0.5–6 c/sec filter surpasses a certain level the gate is blocked, independently of the action of the 8–15 c/sec filter. Thus the timing pulses can pass the gate only if

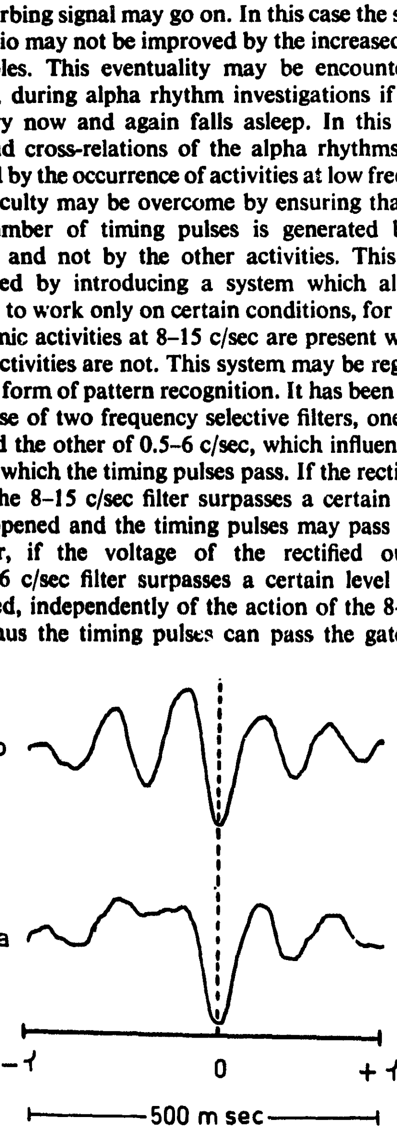

Fig. 7

Comparison of auto-relations obtained with (*b*) and without (*a*) the frequency selection method. Distortion of auto-relation of alpha rhythm in *a* is due to activity at low frequencies taking place during some periods of the computation. In *b* the computation was blocked during these periods.

8–15 c/sec activity is present while 0.5–6 c/sec is not. This is called the Frequency Selection Method (FSM). An improvement of the signal-to-noise ratio obtained with this method is shown in Fig. 7, which shows an auto-relation of an alpha rhythm recorded in a dog that was sleepy. If the dog shut his eyes an alpha rhythm occurred but often after 10–20 sec it disappeared and activities at low frequencies arose while the animal was falling asleep. Fig. 7, *a* shows an auto-relation of the alpha rhythm without FSM. The study of this curve is difficult because the auto-relation is composed of the alpha rhythm and the waves at low frequencies. Fig. 7, *b* shows the auto-relation of the same alpha rhythm, but with FSM. The auto-relation of the alpha rhythm has improved considerably due to the disappearance of components corresponding to low frequencies.

DISCUSSION

One of the points to be discussed is how far relation analysis compares with other analysis methods, in particular with correlation analysis. The latter is determined by a mathematical expression (see Brazier and Casby 1952; Barlow 1959) which is not applicable to relation analysis and therefore the two methods differ. Relation analysis, like many other methods, is a form of extraction of information. The information extracted with auto- and with cross-relation is not the same. Therefore, they will be discussed separately.

Auto-relation is carried out mainly to detect and study rhythmic phenomena; so far as this is concerned it resembles frequency analysis. With auto-relation it is possible also, however, to obtain an average of non-rhythmic, randomly recurring, phenomena if these are large enough in relation to other activities to generate a sufficient number of timing pulses.

Cross-relation is carried out mainly to detect mutual dependence between two signals and their time relations. The signals may be rhythmic or non-rhythmic, as in auto-relation, so long as a sufficient number of timing pulses is obtainable from the phenomena under study.

An advantage of *correlation* analysis is that the signal under study may be very small in relation to other activities. If this signal is present at all the correlograms will bring it to light if the analysis time is sufficient. This does not apply to relation analysis; if the signal under study is too small in relation to other activities, too many timing pulses are generated by these and the signal under study disappears. As shown in Fig. 5, a signal-to-noise ratio of 1:2 is still acceptable. At a signal to noise ratio of 1:5, however, the auto-relation no longer adequately represents the signal.

An advantage of relation analysis is that the apparatus is easily constructed, particularly if an average response computer is available. So far as this is concerned the method may be regarded as an elaboration of average response computing. Even if no automatic computer is available some indication of auto- and cross-relations may be obtained by the use of an ordinary cathode ray oscillograph, as shown in Fig. 2.

If the method is used for determining the average form of non-rhythmic, randomly recurring, phenomena the parts of the phenomena preceding the timing pulses are lost. These parts may be regained by the introduction of negative time, as applied in Fig. 6 and 7.

The use of the frequency selection method improves signal-to-noise ratio, as shown in Fig. 7. This simple form of pattern recognition may be applied to any analysis of activities which change with varying conditions. The method has been applied, for instance, when studying average responses to peripheral stimuli while the subject is in a chosen condition and only if this condition coincides with certain recordable phenomena. The computer may be activited or inhibited by phenomena such as alpha rhythms, lambda waves, hippocampal theta rhythms, activities at low frequencies, etc., or any combination of these.

SUMMARY

A comparatively simple method is described which enables the determination of certain relations between different EEG signals. In distinction from auto- and cross-*correlation* the method is named auto- and cross-relation.

By means of auto-relation analysis an indication is obtained of the rhythmicity of an activity or of the average wave form of a recurring isolated phenomenon.

By means of cross-relation analysis certain relations between different signals, and their time or phase relations, may be studied.

The averaging may be carried out by means of any average response computer.

A simple form of pattern recognition is described for increasing the signal to noise ratio by means of a frequency selective method.

RÉSUMÉ

UNE MÉTHODE D'ANALYSE DE L'EEG PAR AUTO- ET CROSS-RELATION

Les auteurs décrivent une méthode relativement simple qui permet de déterminer certaines relations entre différents signaux EEG. Pour la distinguer des méthodes d'auto- et cross-*correlation*, cette méthode est dénommée auto- et cross-relation.

Par l'analyse auto-relation, on obtient une indication de la rythmicité d'une activité ou de la morphologie moyenne d'un phénomène isolé répétitif.

Par l'analyse cross-relation, on peut étudier certaines relations entre différents signaux, et leur relation temporelle ou de phase.

La moyenne peut être faite grâce à un calculateur de réponses moyennes.

Les auteurs décrivent un moyen simple de reconnaissance de type d'activité, pour accroître le rapport signal-bruit grâce à une méthode de sélection de fréquence.

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