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The Within-Pair EEG Similarity of Twins Reared Apart

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Summary. Within the broader context of our investigations into the heredity of the human EEG, we analysed the EEGs of 28 pairs of monozygotic and 21 pairs of dizygotic twins who were separated as infants and reared apart. The principal goal of this study was to determine the degree to which environmental factors possibly influence the development of a person's EEG. Monozygotic twins reared apart were, with respect to their EEGs, only slightly less similar to each other (if there is any difference at all) than the same person is to himself over time. For dizygotic twins reared apart, we verified the findings of our previous study, namely, that the average within-pair similarity of EEGs estimated from a sufficiently representative sample of fraternal twins was significantly higher than the average inter-individual similarity of EEGs obtained from unrelated persons. The results on both monozygotic and dizygotic twins, yielded conclusive proof that the individual EEG pattern is predominantly determined by hereditary factors.

Key words: EEG – Genetics – MZ/DZ twins reared apart – Within-pair similarity

Introduction

The large number of twin studies carried out over the past 5 decades emphasizes the role of heredity in the human EEG. There seems to be ample evidence that inter-individual differences in background EEG are primarily determined by genetic factors. Environmental conditions, however, both in their physical and social aspects, could have considerable impact on the development of EEG during maturation and, as a consequence, the pronounced EEG similarity in monozygotic (MZ) twins could be caused by the shared, i.e. identical, environmental setting during the years of growth. Principally, there is no way to decide upon the existence or magnitude of such an environmental EEG component by means of the ordinary twin method.

Several attempts have therefore been made to determine the within-pair EEG similarity of MZ twins who were separated as infants and reared apart (Newman et al. 1937; Juel-Nilsen and Harvald 1958; Juel-Nielsen 1965; Shields 1962). Although the results of these classic studies have generally confirmed the importance of genetic determinants of the spontaneous EEG, previous work can be justifiably criticised as being restricted (1) to an insufficient mathematical representation of the individual EEG characteristics and (2) to relatively small sample sizes with an average age at reunion of only 12 years.

Hence, in the broader context of our investigations into the heredity of the human EEG (Table 1), we pursued anew, by means of an improved method of analysis, the question: to what degree are the individual characteristics of the normal EEG due to genetic factors? The present study of MZ (and dizygotic DZ) twins reared in different environments (mean age at separation: 0.3 years; mean age at reunion: 23.9 years) is one of the largest and certainly the most extensive ever done with reunited twins (Lykken 1982; Lykken et al. 1982).

Method

According to our findings from previous studies (Stassen 1980, 1985; Stassen et al. 1982, 1987), EEG spectral patterns, with a specificity and reproducibility of > 90% each, largely meet the requirements of genetic EEG studies. These spectral patterns[1],

[1]Spectral patterns are analogously defined like feature vectors in the field of Pattern Recognition

Table 1. Overview of investigations into the genetics of the human EEG at Zurich

	Genetic aspects of the EEG, studies at the Psychiatric University Hospital Zurich	
1981/1982	Calibration study, 2 measurements from the same individual at 14-day intervals	81 healthy volunteers
1986	Twin study I,[1] MZ/DZ[3] twins reared together	48 MZ twins, 50 DZ twins
1986/1987	5-Year follow-up, 2 measurements from the same individual at 14-day intervals	30 healthy volunteers
1987	Twin study II,[2] MZ/DZ twins reared apart	56 MZ twins, 42 DZ twins
1988	Family study,[1] measurements from complete families	36 families

[1] In collaboration with Bonn (FRG)
[2] In collaboration with Minneapolis (USA)
[3] MZ, monozygotic; DZ, dizygotic

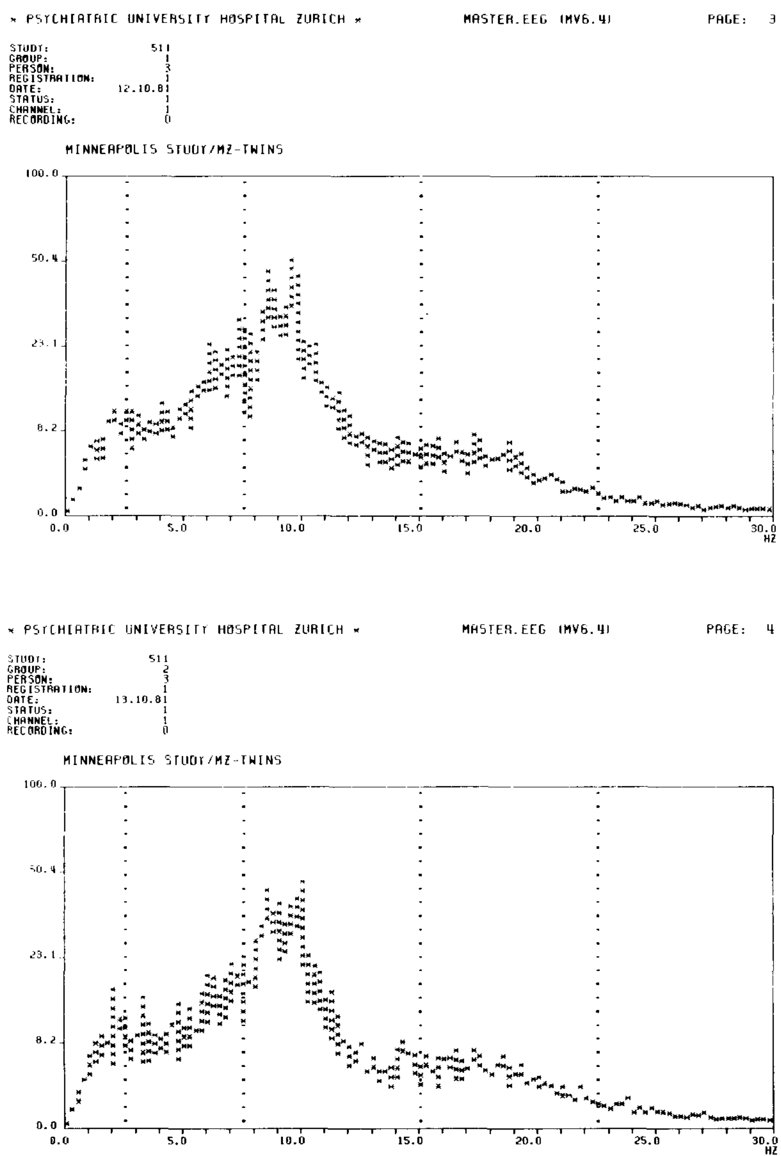

Fig. 1. Pair of MZ male twins reared apart, 38 years old (Tom/Eric). The spectral intensities are plotted on a log-proportional scale along the vertical axis

whose characteristics have recently been discussed in detail (Stassen et al. 1987), were the basic elements of our similarity approach to EEG analysis. In connection with a set-theoretical similarity function, this approach provided for systematic within-pair, inter-individual and intra-individual comparisons of brain waves, thus enabling, with respect to investigations into the within-pair similarity of MZ or DZ twins, a quantitative comparison of two distributions: the distribution of within-pair

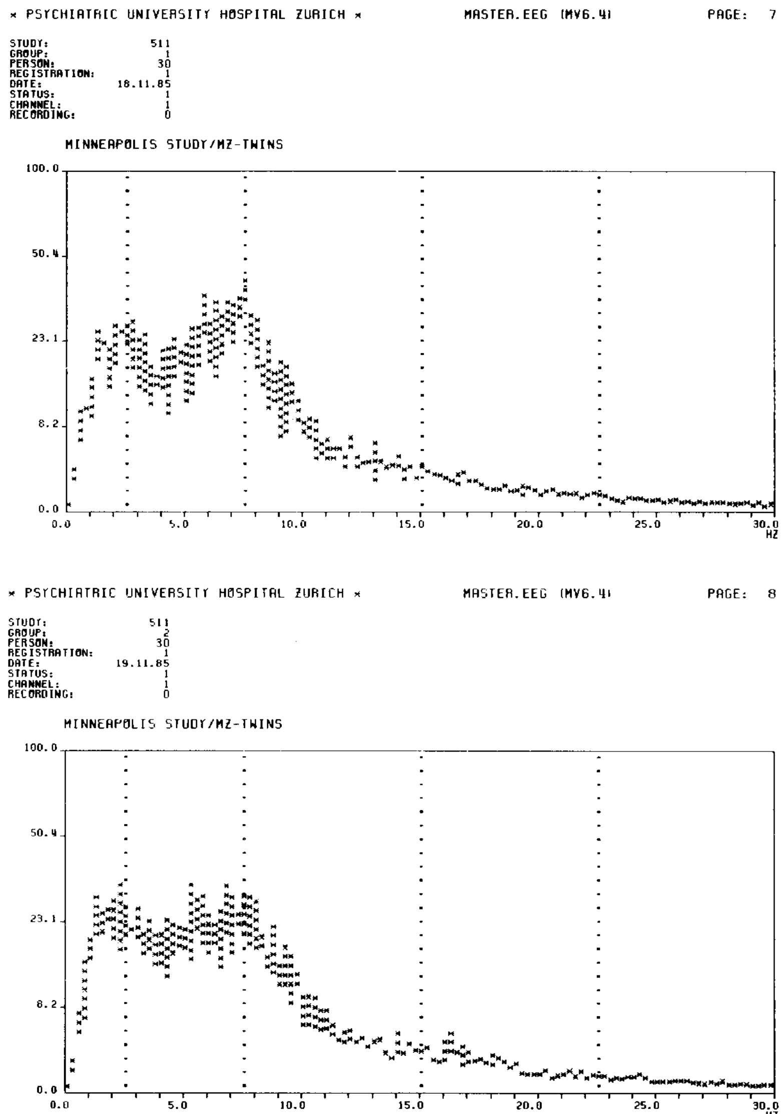

Fig. 2. Pair of MZ female twins reared apart, 41 years old (Sylvia/Carol). The spectral intensities are plotted on a log-proportional scale along the vertical axis

similarities against the reference distribution[2] of inter-individual similarities.

The chosen set-theoretical similarity function s measured the normalized common volume of 2 patterns n and m taking differences in the significance of information into account by weighting the corresponding frequency bands appropriately

$$s(n, m) = \sum_k W(k) \left[\frac{|n \cap m|}{|n \cup m|}\right]_k; \qquad \sum_k W(k) = 1$$

Here $W(k)$ was the weight of the k-th frequency band, $|n \cap m|$ the cardinality of the set-theoretical intersection, and $|n \cup m|$ the cardinality of the set-theoretical union of the 2 patterns n and m. These cardinalities were calculated by counting the volume elements which were shared by the 2 patterns and, by counting the total number of volume elements involved, respectively. The notation $[\bullet]_k$ indicated the restriction of the latter operations to the k-th frequency band. All free parameters of the similarity function (number of frequency bands, weights) were determined by means of an optimization algorithm. As criterion for optimization, we used the discrimination between the distribution of inter-individual and intra-individual similarity coefficients and minimized the overlap between the 2 distribution curves.

We employed three equally weighted frequency bands: 0–7.5 Hz, 7.5–15 Hz and 15–32 Hz, which was a slightly simplified selection of frequency bands compared with the solution of 0–2.0 Hz, 2.0–3.75 Hz, 3.75–7.5 Hz, 7.5–15 Hz and 15–30 Hz originally suggested by our optimization algorithm.

The distribution of inter-individual similarities (derived from unrelated persons) reflected the full variety of possible coincidences between brain wave patterns found in the general population. Due to the fact that inter-individual similarities are normally distributed and, consequently, the distribution can be characterized by the two parameters, mean and standard deviation (μ and σ, respectively), we expected, for example, 90% of comparisons to have an inter-individual similarity s of magnitude

$$\mu - 1.64\sigma \leq s \leq \mu + 1.64\sigma$$

[2]From a methodological point of view, it is worth noting that the reference distribution should also be estimated from the basic twin sample by analysing all possible combinations of unrelated persons, thus eliminating the need for an additional set of EEGs to be registered under identical experimental conditions

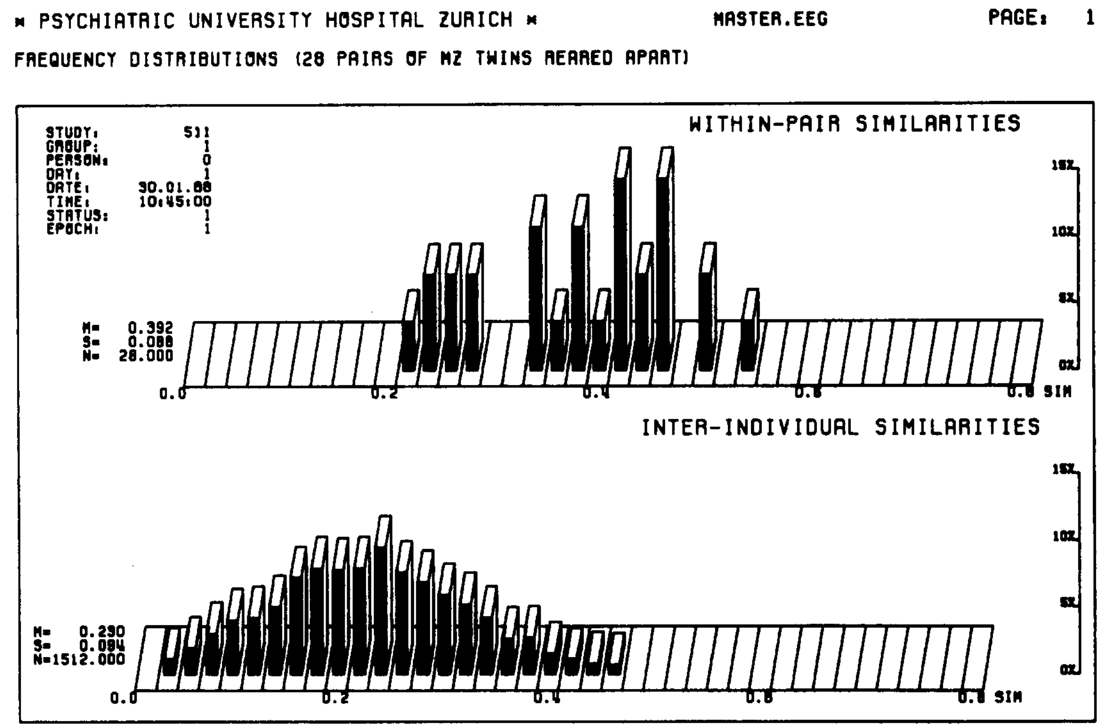

Fig. 3. The discrimination between the distributions of inter-individual *(left)* and within-pair *(right)* similarity coefficients based on 28 pairs of MZ twins reared apart

On the other hand, every within-pair EEG similarity *s*' of MZ twins reared together was well above the mean value μ which applied to the general population. The measured within-pair similarities were even comparable in magnitude with those derived from repeated registrations of the same person (Stassen et al. 1987).

As to the within-pair EEG similarity of DZ twins, one would expect under the assumption of a strong genetic EEG component and, for a sufficiently representative sample of DZ twins, a distribution of similarity values which varied from striking coincidence (comparable to that of MZ twins) to complete dissimilarity. Indeed, this was the result of our recent study with DZ twins (Stassen et al. 1987). However, this was the first time that this fact – though expected – was confirmed. Therefore, it was of particular interest to replicate these findings on the basis of another sample of DZ twins.

The Twin Sample

Between 1980 and 1987, a considerable number of twins reared apart had been invited to Minneapolis where they were extensively tested psychologically during a full week. As part of the psychophysiological battery of this study, the resting EEGs of all probands were recorded for a 5-min period. This work was carried out under the auspices of Professor T. Bouchard from the Department of Psychology at the University of Minnesota. The EEGs of some of these twins had already been analysed a few years previously (Lykken et al. 1982) and have been included in the present study in order to be re-analysed with our improved method of approach.

Our sample comprised 48 pairs of healthy adult twins, of which 28 were MZ (mean age 40.9 years; 9 male and 19 female pairs) and 21 were DZ of the same sex (mean age 42.2; 6 male and 15 female pairs). Zygosity was established by standard anthropological methods: fingerprint ridgecount, ponderal index and analysis of 20 serological markers. The occipital resting EEGs were recorded with eyes closed (unipolar leads) and stored on analogue tape. In a second step, 20-s epochs were selected visually and marked with an artefact-code if necessary. All signals were digitized[3] with 10-bit resolution at a frequency of 256 Hz, Fourier-transformed and analysed according to the similarity conception described previously or, in more detail, elsewhere (Stassen 1985).

Results

Visual inspection of EEG spectral patterns (as 2-dimensional plots) revealed, on the one hand, the strik-

[3]Mr. W. Manske performed the coding of data and artefacts, Mr. K. Heroian was responsible for the analogue/digital data conversion. The program system and the data bank were installed on an IBM 3033/MVS

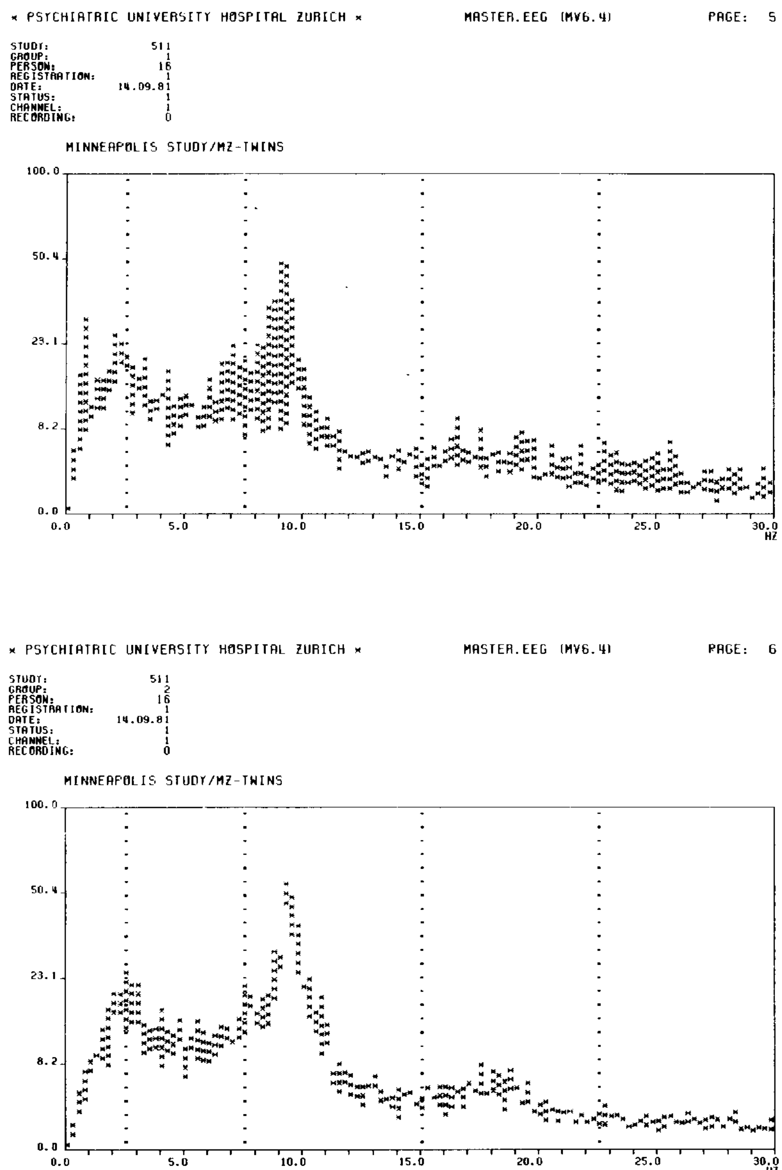

Fig. 4. Pair of MZ twins reared apart, 23 years old (Roy/Paul). The upper pattern is computed from EEG time series disturbed by considerable muscle artefacts. The spectral intensities are plotted on a log-proportional scale along the vertical axis

ing within-pair similarity of EEGs obtained from MZ twins reared apart (Figs. 1 and 2). On the other hand, the same plots also gave a clear impression of the distinct individuality of the human EEG as expressed by the overwhelming variety of pattern forms (cf. Fig. 4, 5 and 6). In addition to this more qualitative information, our method of approach specially provided for a quantitative analysis of hereditary factors by comparing the 2 distributions of inter-individual similarity coefficients taken from all possible combinations of unrelated individuals, and within-pair similarity coefficients taken from all pairs of MZ or DZ twins reared apart.

All distributions of similarity coefficients (Figs. 3 and 7) were estimated from the raw frequencies of 50 disjoint, equally spaced classes into which the defining interval [0,1] of the similarity coefficient was partitioned. Finally, these raw data $f(k)$ were transformed into relative frequencies $f'(k)$ (percentages)

$$f'(k) = f(k) * 100/\sum_i f(i)$$

which allowed direct comparison of distribution curves. However, in the case of within-pair similarities, one has to take into account the fact that the estimates originated from a relatively small set of similarity coefficients. The resulting distribution curves were therefore characterized by several holes and were not as clearly formed as those of the inter-individual similarities (the latter distribution curves were based on a sufficiently large set of similarity coefficients).

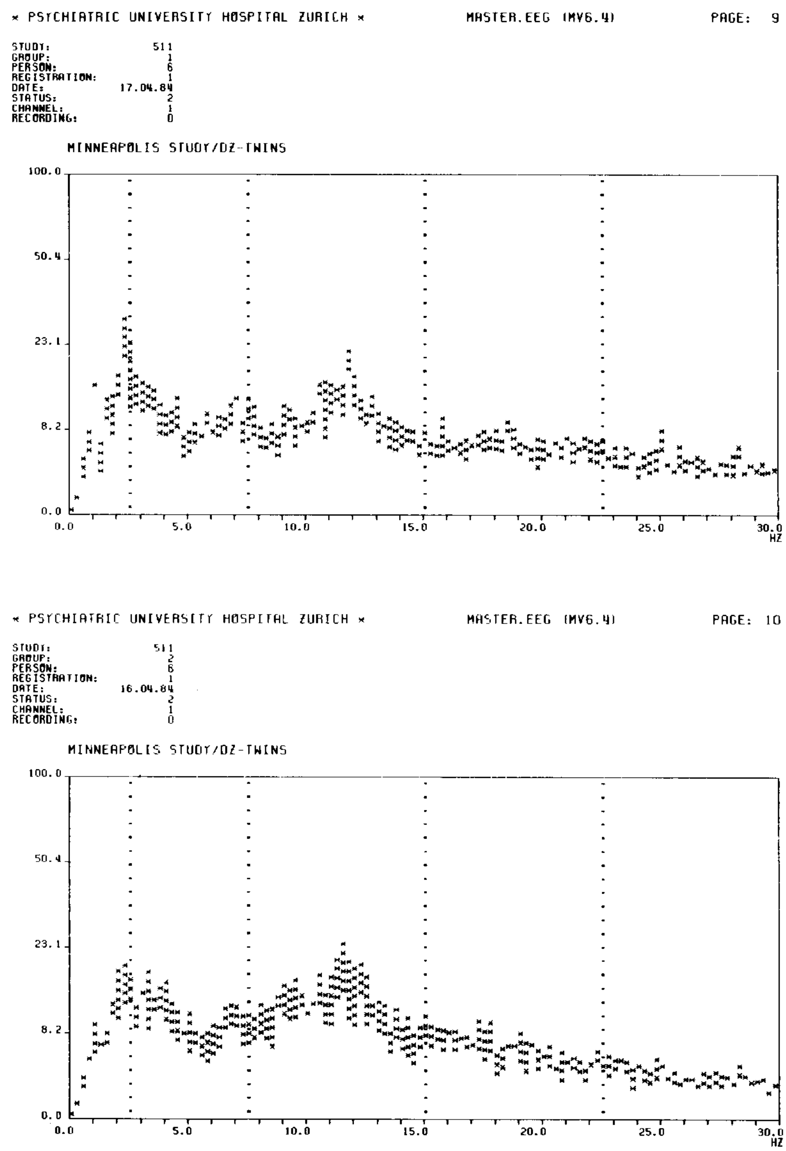

Fig. 5. Pair of DZ male twins reared apart, 30 years old (Melvyn/Paul). The spectral intensities are plotted on a log-proportional scale along the vertical axis

Comparing the within-pair similarities of MZ twins reared apart with the distribution of inter-individual similarities of unrelated individuals, Fig. 3 provides clear evidence for a high coincidence between the EEGs of MZ twins reared apart, reflected, for example, by mean values whose differences were highly significant. However, there were 7 pairs which did not fit the picture of expected high within-pair similarity (4 isolated bars at the left side of distribution curve). Detailed analysis showed that these lower values of within-pair similarities, which were nevertheless above the average inter-individual similarity, were in 5 cases due to the fact that the EEGs of one or both co-twins were considerably disturbed by muscle artefact (1 of these pair is displayed in Fig. 4). In 1 case, the deficiency of within-pair similarity was due to an almost complete lack of α activity in one co-twin (the corresponding patterns were otherwise in good coincidence) and, in another case, serious vigilance problems appeared in the EEG of one co-twin.

The discriminating power between the 2 distribution curves (which was inversely proportional to the relative overlap of the 2 curves) was 79.8%, based on 8 epochs of 20 length and 1 channel (Cz) only.

We therefore expected, according to the findings of our pilot study with healthy subjects, that a replication of this twin study with our standard design (4 or more channels, use of our cap which guarantees identical electrode positions for both co-twins) would improve the discriminating power by about 6%. Thus, our findings suggested that MZ twins reared apart were, with respect to their EEGs, only slightly less similar to each other (if there is any difference at all)

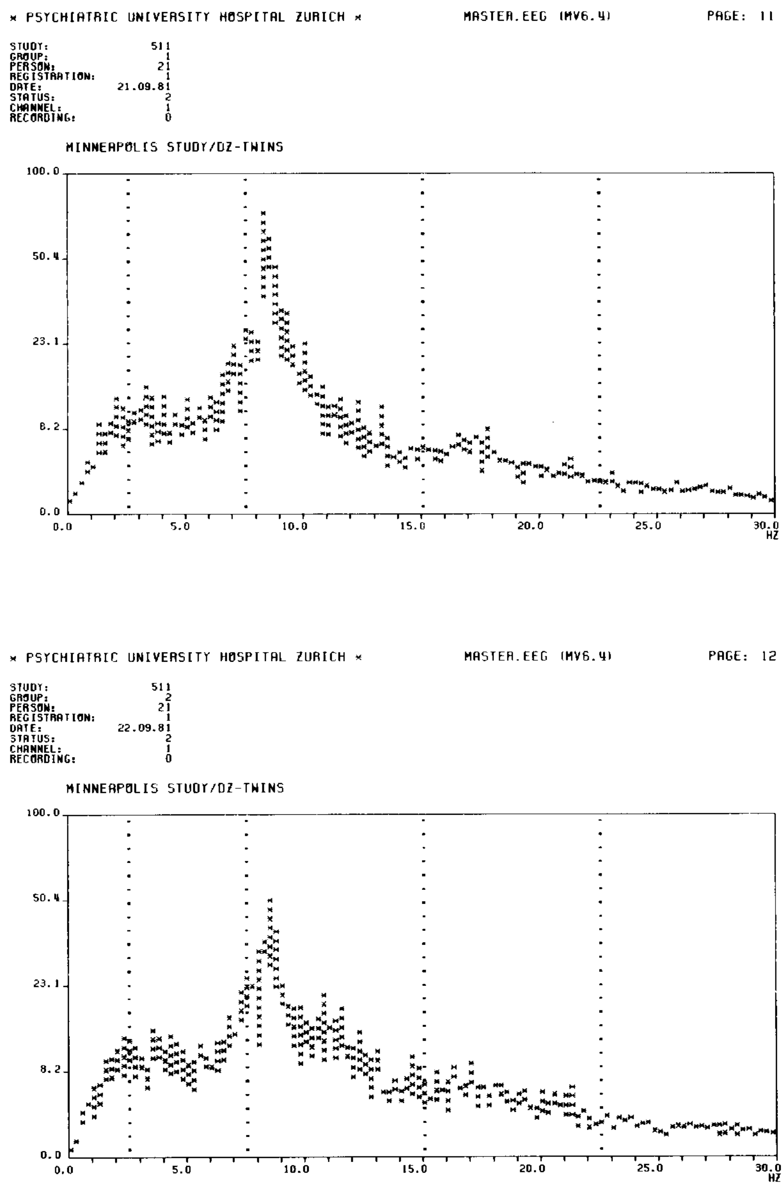

Fig. 6. Pair of DZ female twins reared apart, 43 years old (Margaret/Eleanor). The spectral intensities are plotted on a log-proportional scale along the vertical axis

than is the same person to himself over time. The other important goal of our present study was the verification of our findings on DZ twins, namely, that the average within-pair similarity of EEGs estimated from a sufficiently representative sample of fraternal twins was significantly higher than the average inter-individual similarity of EEGs obtained from unrelated persons. For this purpose, we analysed the DZ twin data following the same procedure as in the MZ case. Visual inspection of resulting spectral patterns showed that the within-pair similarity varied, as expected, from striking similarity (comparable to that of MZ twins) to complete dissimilarity: there were 14 pairs of DZ twins whose within-pair similarities were well above the average similarity between unrelated individuals whereas the within-pair similarity of 7 pairs was comparable to that of unrelated individuals.

In a second step, we again performed systematic inter-individual and within-pair comparisons of patterns in order to determine the underlying distributions of similarity coefficients. Figure 7 illustrates the visual impression concerning the within-pair similarity of DZ twins: the coefficients were spread over a broad range and reflected a variation from striking similarity to complete dissimilarity. But, as a whole, they yielded a distribution curve which was highly different from that of the inter-individual similarities of unrelated persons. This result was again based on 8 epochs of 20 s length and 1 channel (Cz) only.

These findings confirmed the results of our previous study on DZ twins. Moreover, the results of our

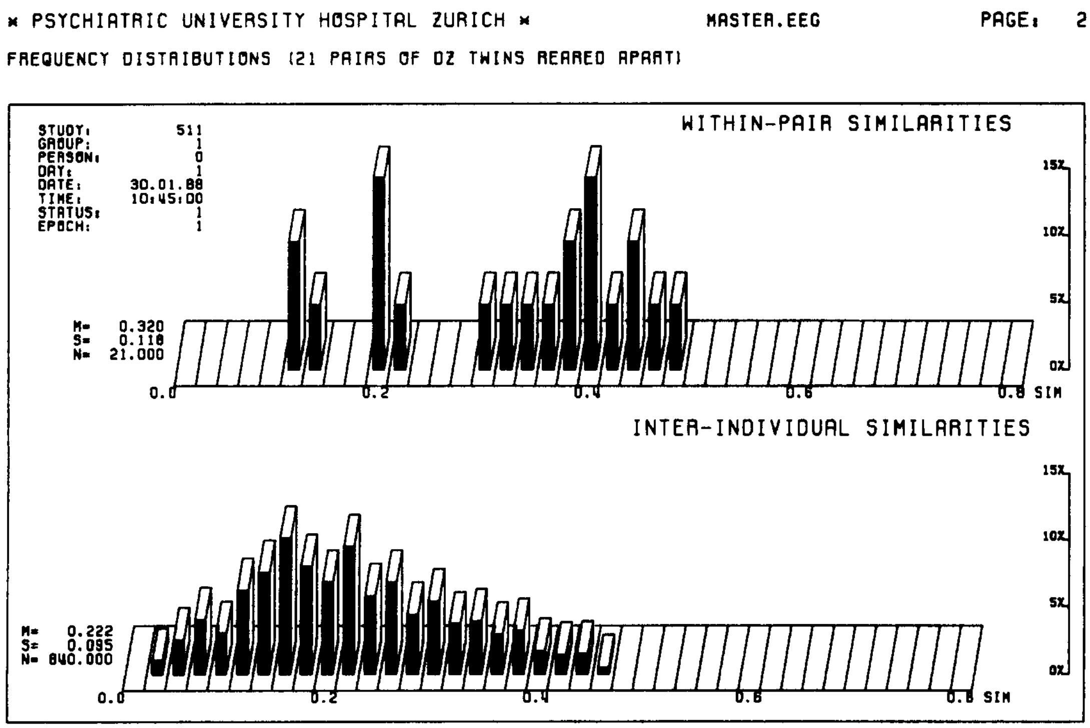

Fig. 7. The discrimination between the distributions of inter-individual *(left)* and within-pair *(right)* similarity coefficients based on 21 DZ twins (of the same sex) reared apart

investigation into the within-pair similarity of twins reared apart (and who, consequently, were exposed to different environmental influences) yielded conclusive proof that the individual EEG pattern is predominantly determined by hereditary factors.

Discussion of Results

Within the broader context of our investigations into the heredity of the human EEG, we developed a new computerized method of analysis which was especially designed to measure the distinct individuality of brain wave patterns (computerized recognition of individuals by EEG spectral patterns). The basic quantities of this approach – the spectral patterns – proved to be well-suited to genetic questions with respect to reproducibility and specificity. Consequently, our recent study with MZ and DZ twins reared together revealed presumptive evidence for a strong genetically determined component of the human EEG. Based on these findings, we started our present investigation into the within-pair similarity of MZ and of DZ twins reared apart in order to broach the question to what degree are the individual characteristics of the normal EEG due to genetic factors, by excluding environmental factors shared by each pair of co-twins. In terms of the applied similarity conception, the central question of this study actually contained 3 sub-questions:

(1) Is the within-pair EEG similarity of identical twins reared apart significantly lower than the within-pair EEG similarity of identical twins who shared the same environment during the years of growth?
(2) If there exists a significant impact from environmental factors, what is the relative magnitude of the genetic EEG component?
(3) Is the average similarity of EEGs estimated from a sufficiently representative sample of fraternal twins reared apart significantly higher than the average inter-individual EEG similarity of unrelated individuals?

The empirically derived distributions of similarity coefficients impressively confirmed earlier findings in the literature: the distinct individuality of the spontaneous EEG is indeed primarily determined by genetic factors. This qualitative outcome of the present study is reflected (1) by a discriminating power (relative overlap) of 79.8% between the distribution of within-pair MZ similarity coefficients and the distribution of inter-individual similarities and (2) by 14 pairs of DZ twins (66.7%) whose within-pair similarity was well above the average inter-individual similarity of unrelated individuals. The slightly smaller number of DZ pairs with highly coincident EEG patterns (10 pairs, 47.6%) was not statistically different from that (52%) of our recent study on DZ twins reared together. Indeed, the true rate of highly coincident DZ twins (with respect to their EEGs) is sample-dependent because, for example, as Vogel (1970) showed, the heredity of the human EEG depends on the specific EEG variant.

As to the quantitative outcome of this study, one has to take the following limitations into account. Since each twin pair was exhaustively tested psychologically during a whole week, the full potential of psychophysiological measurement could not be utilized. In particular, only 2 EEG channels were recorded. Therefore, the distribution of inter-individual similarity coefficients was somewhat different from those of previous studies. Nevertheless, the results of our calibration study with healthy subjects suggested that the corresponding distribution based on 4 or more channels would improve the discriminating power by about 6%[4]. This implied that the EEGs of MZ twins reared apart were as similar to each other as the EEGs of the same person over time.

Thus, our present findings show the necessity for a replication of twin studies under optimal experimental conditions in order (1) to take advantage of the power and high resolution of the proposed mathematical approach and, (2) to improve the quantitative description of the phenomena under discussion. Accordingly, we are planning a new twin study under these conditions.

[4]The similarity approch to EEG analysis is based on distributions of similarity coefficients inherent to a specific genetic problem whereby the corresponding set of inter-individual EEG similarities serves as reference distribution. Hence, the similarity distribution under discussion, namely that of MZ or DZ similarity, is tested against a reference originating from the same registrations. Due to this conception, which aims at the relation between a problem-specific distribution and its reference, even a direct comparison of results derived by studies with different technical design (e.g. unipolar versus bipolar registrations) is possible

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