Brain Mapping of Visual Evoked Activity - Topographical and Functional Components

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Abstract- Electroencephalographic (EEG) and evoked activity can be recorded non-invasively in order to monitor human brain activation online. Electrical fields are generated by large intracranial neural populations and spread to the scalp through volume conduction. All measured signals depend on the location of the recording and reference electrodes. Simultaneous recordings from many scalp positions allow for a topographical assessment of the complete electrical fields of the brain and avoid problems typically seen with time series analysis.

The present contribution will illustrate the fundamentals of topographic mapping of human electrophysiological brain activity as well as quantitative analysis methods. Visual evoked potential data obtained in a group of 12 healthy adults are presented. We will focus on the definition and identification of evoked components that represent steps in visual information processing. In addition, the application of statistical data reduction techniques are described, and the results of functional components which are related to experimental variations are discussed.

Key Words: Brain electrical topography, Visual evoked potentials (VEP), Global field power, Spatial principal components analysis

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INTRODUCTION

Human visual information processing can be studied by non-invasive measurements of electrical brain activity that reflect mass activity originating simultaneously from many neurons. Commonly we use scalp recordings in healthy volunteers and patients in order to find neural correlates of per-ceptual or cognitive processing, and only in rare cases (like before surgery for epilepsy or during tumor removal) it is possible to perform intracranial recordings in patients[1].

One prerequisite for recordings of EEG and evoked brain activity is the propagation of field potentials that arise from large neuronal populations through volume conduction. Brain activity can be detected at the scalp by relatively large electrodes when many neurons are activated synchronously. Only activity originating from so-called “open” intracranial electrical fields can be

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assessed by scalp recordings, and in contrast to this, "closed" electrical fields are formed by populations of neurons arranged so that electrical activity cancels. Such a constellation is found in many subcortical structures, consequently their neural activity is inaccessible to distant mass recordings. The geometry of the neuronal generators accounts for differences between neural subsystems: for example, auditory evoked brain stem potentials arising from deep structures can be detected by scalp recordings while similar subcortical activity (generated in the thalamus or superior colliculi) can not be measured from the outside when visual stimuli are presented. The reason for this difference is due to the arrangement and orientation of the intracranial electrical field formed by groups of neurons in the corresponding subcortical structures.

The major neuronal source for electrical activity that is detectable on the scalp form the pyramidal cells which are located in the cortical layers: these neurons are arranged in parallel perpendicular to the cortical surface which, however, is folded in intricate ways so that the generators cannot be assumed to be perpendicular to the outer surface of the brain.

The research employing evoked activity aims at elucidating brain mechanisms related to sensory or cognitive processing while the subject is involved in perceptual or cognitive tasks. Like most neurophysiological experiments on human subjects, the topographical analysis of electrical brain activity is employed as a method to detect covariations between experimental conditions that are systematically controlled by the investigator and features of the recorded brain activity. Evoked scalp potential fields yield information on a number of partly independent neurophysiological parameters such as component latency that indicates neural processing time, or field strength indexing the amount of synchronous activation of a neuronal population engaged in stimulus processing and during the execution of cognitive tasks.

Measures derived from such data are used as unambiguous descriptors of electrical brain activity, and they have been employed successfully to study visual information processing in man[2,3]. The aim of evoked potential studies is to identify so-called components of electrical brain activity that are defined in terms of latency with respect to some external or internal event and in terms of topographical scalp distribution patterns. Irrespective of whether the exact intracranial generator populations can be determined, the interpretation of scalp potential data combined with the knowledge on the anatomy and physiology of the human central nervous system may allow to draw useful physiological interpretations[3].

Scalp topography is taken as a measure that characterizes electrical brain activity quantitatively in terms of component latency, neural response strength, and scalp location. The comparison of scalp potential fields obtained in different experimental conditions (e.g., different physical stimulus parameters, different subjective or psychological states, or normal vs. pathological neurological traits) may be employed to test hypotheses about the characteristics of the neuronal populations activated. As a basic physical fact we know that identical scalp potential fields may or may not be generated by identical neuronal populations while non-identical potential fields must be caused by different intracranial generator mechanisms. Thus, we are interested in variations of scalp potential fields caused by the manipulation of independent experimental parameters, and we can interpret the co-variation of electrical brain activity in a physiologically reasonable way.

In the present review we are concerned with the analysis of the scalp distribution of visually evoked electrical brain activity with only little consideration of the exact locations of the underlying neural structures. For a survey over the localization of intracranial processes and human electrophysiological signals (EEG and event-related brain activity), the reader may consult a recent publication[4]. We will present visual evoked potential data obtained in a group of 12 healthy adults, and we will focus on the definition and identification of evoked components that represent steps in visual information processing. In addition, the application of statistical data reduction will be described.

Electrophysiological mapping is related to other methods: with modern imaging techniques (CT, structural or functional MRI, PET), the determination of

anatomical brain structures or of hemodynamical responses to different processing demands is available at high spatial resolution, but typically one has to rely on longer integration times in order to derive significant signals that reflect changes in metabolic responses. Different from imaging methods like functional MRI or PET, the electrophysiological measurements of spontaneous EEG and evoked potential fields (or of the accompanying magnetic fields, MEG) possess very high temporal resolution in the order of milliseconds. Thus, techniques to quantify electric brain topography are unsurpassed when functional validity is required in order to characterize central nervous processing in humans. All relevant neural processing related to perception, cognition, or motor activation takes place in the split-second range that can be tapped very efficiently with electrophysiological recordings.

We also note that electrical measurements are relatively easy and inex-pensive to perform, and they also offer the possibility to directly assess brain function in real life situations without referring to indirect comparisons between experimental and neutral baseline conditions or between different task demands which is the basis for functional brain imaging studies.

BASIC IDEAS OF TOPOGRAPHIC BRAIN MAPPING

Electrical brain activity is recorded from discrete points on the scalp against some reference point, and conventionally such data have been analyzed as time series of potential differences between pairs of recording points. Multichannel recordings allow to assess the complete, topographical distribution of electrical brain activity. For a 2-D display, waveform patterns are transformed to images of the electrical landscape of brain activity at discrete time points. In a similar way, the results of frequency analyses of the recorded EEG can be displayed. The result of topographical transformations is a map that shows the scalp distribution of brain activity at discrete time points (or for given frequencies of spontaneous EEG). Such functional imaging is very sensitive to state changes and processing demands of the organism, and it possesses high time resolution needed to study brain processes. With mapping techniques, sequences of neuronal activation patterns can be characterized non-ambiguously, and statistical data analyses can be performed on such data.

Mainly for historical reasons and due to technical limitations, electrophysiological results were often illustrated and analyzed as univariate time series. Only the technical advancement allowed for simultaneous acquisition of data in many channels simultaneously, thus enabling the treatment of EEG data as potential distributions[2,5,6]. The advantage of mapping of brain activity lies not just in the display of brain activation in a topographical form but mapping is a prerequisite of an adequate analysis of brain activity patterns.

Since electrophysiological signals are recorded as potential difference between recording sites, the location of the reference electrode will drastically influence the shape of activity recorded as time series. Because potential maps are reference-independent, mapping and quantitative topographical analyses of EEG and evoked brain activity avoid the fruitless discussion about an electrically neutral reference point[7].

Conventional visual evoked potentials (VEPs) are illustrated as potential waveforms in Fig. 1. Activity was elicited by checkerboard reversal stimuli presented to the center or to the left or right hemiretina (1.2º checks, 13º $\times$8.4º test field, 95% contrast, 3.19 reversals/s), and recordings were obtained with electrodes overlying the occipital brain regions of the left and right hemisphere. Some of the waveforms clearly display a negative component at about 80 ms followed by the classical P100 component occurring at a latency of about 110 ms but there are vast differences between the waveforms recorded over the left and right hemisphere. This indicates that the topography varies with stimulus condition. As expected, with central stimuli the components appear to be of similar amplitude over both hemispheres while the P100 component is clearly seen over the right hemisphere when the left retinal areas are stimulated (and there is no peak over the contralateral hemisphere) whereas stimuli on the right hemiretina yield largest amplitudes over the left occipital areas. This is in con-

flict with the anatomical pathway of the axons of the retinal ganglion cells: the left half of the retina provides information to the left hemisphere and the right hemiretina is connected to the right hemisphere. Consequently, this finding has been termed "paradoxical lateralization" of visual evoked brain activity[8] since it deviates from what one expects.

The waveforms shown in Fig. 1 are not easy to interpret: for example the VEPs over the ipsilateral hemisphere show a sustained component that reaches a peak between 160 and 200 ms for lateralized stimuli while this is much less clear with central retinal stimuli. The interpretation of such waveforms becomes even more complex when one considers that that the form of the recorded activity is directly determined by the choice of the recording reference. Essentially, from n electrodes, $n \cdot (n-1)$ different recordings are possible, and an exhaustive example that illustrates all possible waveforms of a one data set with a 16 channel recording is given by Lehmann and Skrandies[5]. Different reference points yield different patterns of activity that are refected by the conventional time series. Of course the physiological response of the brain is independent of the choice of the recording reference. The search for a so-called inactive reference point has no practical solution since evoked potential waveforms always constitute measurements of the continuously fluctuating potential gradients between two points whether both on the scalp or not (see also[7,9]). Thus, it is evident that from identical data, different conclusions can be derived, and for a physiologically meaningful interpretation of the recorded data a non-ambiguous analysis method is needed.

For the analysis of the topographical aspects of electroencephalographic activity it is important to keep in mind that we are dealing with electrical fields originating in brain structures whose characteristics vary with recording time and space: the position of the electrodes on the scalp determines the pattern of activity recorded, and multichannel EEG and evoked potential data enables us to analyze topographically the electrical fields that are reconstructed from many spatial sampling points. From a neurophysiological point of view, evoked components are generated by the activation of neural assemblies located in circumscribed brain regions with certain geometric congurations. The analysis of landscapes of electrical brain activity may give much more information than the conventional interpretation of potential waveforms that stresses only restricted aspects of the available electrical data[2,3,10].

As in all sensory modalities, following visual stimulation the brain generates an electrical field originating from neuronal assemblies in the sensory cortex. This

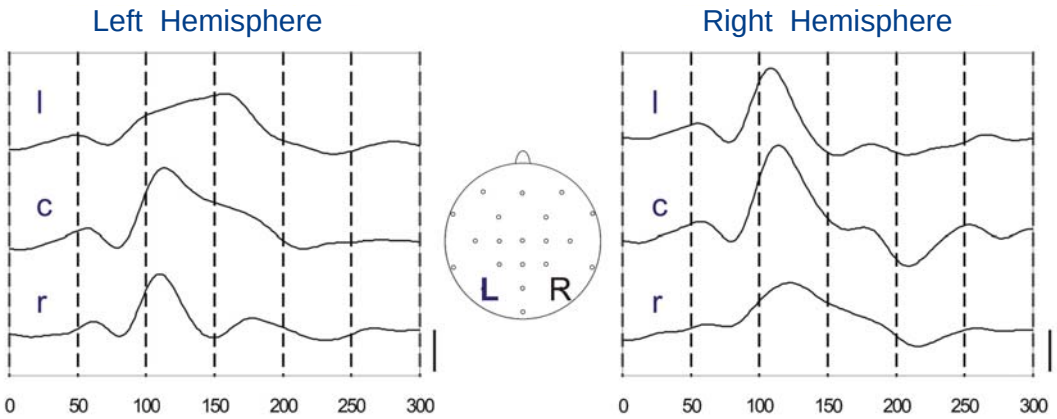

Figure. 1 Potential waveforms evoked by a checkerboard reversal stimulus (1.2º checksize, 13 x 8.4º test field, 95% contrast) recorded over the left or right occipital areas with a frontal reference. The stimuli were presented with central fixation, or to the left or right hemiretina (abbreviated as " l ", " c ", and " r "). The calibration bar corresponds 5μV; positive is up, L = electrode over the left, R = electrode over the right hemisphere. Numbers indicate time after stimulus onset.
Grand mean data from 12 healthy adults with normal vision.

electrical field changes in strength and topography over time. Multichannel recordings yield a complete picture of the data of Fig. 1, and the results of recordings from 29 electrodes are displayed as series of potential distributions in Figs. 2A, B, and C which illustrate the activity pattern elicited by central, or by left or right hemiretinal stimulation. The maps show the potential distribution within the recording array at different time points after stimulation (up to 286 ms after the occurrence of a visual stimulus). At each latency a characteristic topography is elicited. It is important to note that the features of a map do not change when a different recording reference is employed: all topographical characteristics remain identical when the electrical landscape is viewed from different points. This is similar to the constant relief of a geographical map where the sea level is arbitrarily defined as zero level. A change of the reference point changes the labeling of the contour lines but not the landscape in itself. The location of maxima, minima as well as the location and strength of potential gradients in a given map are independent of the reference point that defines zero.

The potential maps illustrated in Fig. 2 were reconstructed from data measured from the electrode array shown in the inset. Twenty-nine electrodes are distributed as a regular grid over the brain regions under study. Since only potential differences within the scalp field are of interest, all data are referred to the computed average reference. This procedure results in a spatial high pass filter, eliminating the DC-offset potential introduced by the necessary choice of some point as recording reference.

It is obvious that the topography as well as the strength of the electrical field change as a function of time, and topography is drastically different with stimuli presented to different retinal areas. This is evident when Figs. 2A, B, and C are compared. Around 110 ms, with central stimulation a symmetrical occipital positivity is seen (Fig. 2A), while with left hemiretinal stimuli (Fig. 2B) this component is located over the right, and with right hemiretinal stimuli it occurs over the left hemisphere (Fig. 2C). Different from the waveform pattern discussed above, this component is not restricted to one hemisphere but it exhibits a broad distribution over the occipital brain areas. In a similar way, lateralized stimuli elicit a scalp field pattern between 140 and 150 ms with a clearly lateralized positivity over occipital areas with is different for left and right hemiretinal stimuli (compare maps at 144 or at 158 ms in Figs. 2B and C). With central stimuli an occipitally positive component occurs with two peaks (one over the left and one over the right hemisphere). This is easy to see in the potential maps, but is cannot be discerned in the potential waveforms illustrated in Fig. 1, and with central stimuli no peaks emerge around 140 or 150 ms latency.

From the inspection of the maps series it is evident that there are times where the field relief is shallow while at other points in time the maps display large voltage peaks and troughs, associated with steep potential gradients. Obviously these time instances indicate strong synchronous activation of neurons in the visual cortex and need to be identified in a quantitative way.

DEFINITION OF COMPONENTS OF BRAIN ACTIVITY

It is important to keep in mind that the absolute locations of the potential maxima or minima on the scalp do not necessarily reflect the location of the underlying generators. This is due to the propagation of the intracranial signals by volume conduction, and it has led to some confusion in the interpretation of EEG data. As has been illustrated, the location of steep potential gradients appears to be more adequate and realistic parameter that reflects intracranial source locations than the scalp position of the extreme values of the potential field[4]. This is confirmed by the results presented in Fig. 2: it is obvious that the potential peaks exhibit a "paradoxical lateralization" at 112 ms whereas the potentials gradients are located over the scalp areas that are expected from anatomy (stimuli presented to the left hemiretina elicit steep gradients over the left occipital regions and right hemiretinal stimuli are followed by pronounced gradients over the right hemisphere, see Figs. 2 B and C).

The topographical analysis should not be restricted to the qualitative display of maps at many time points

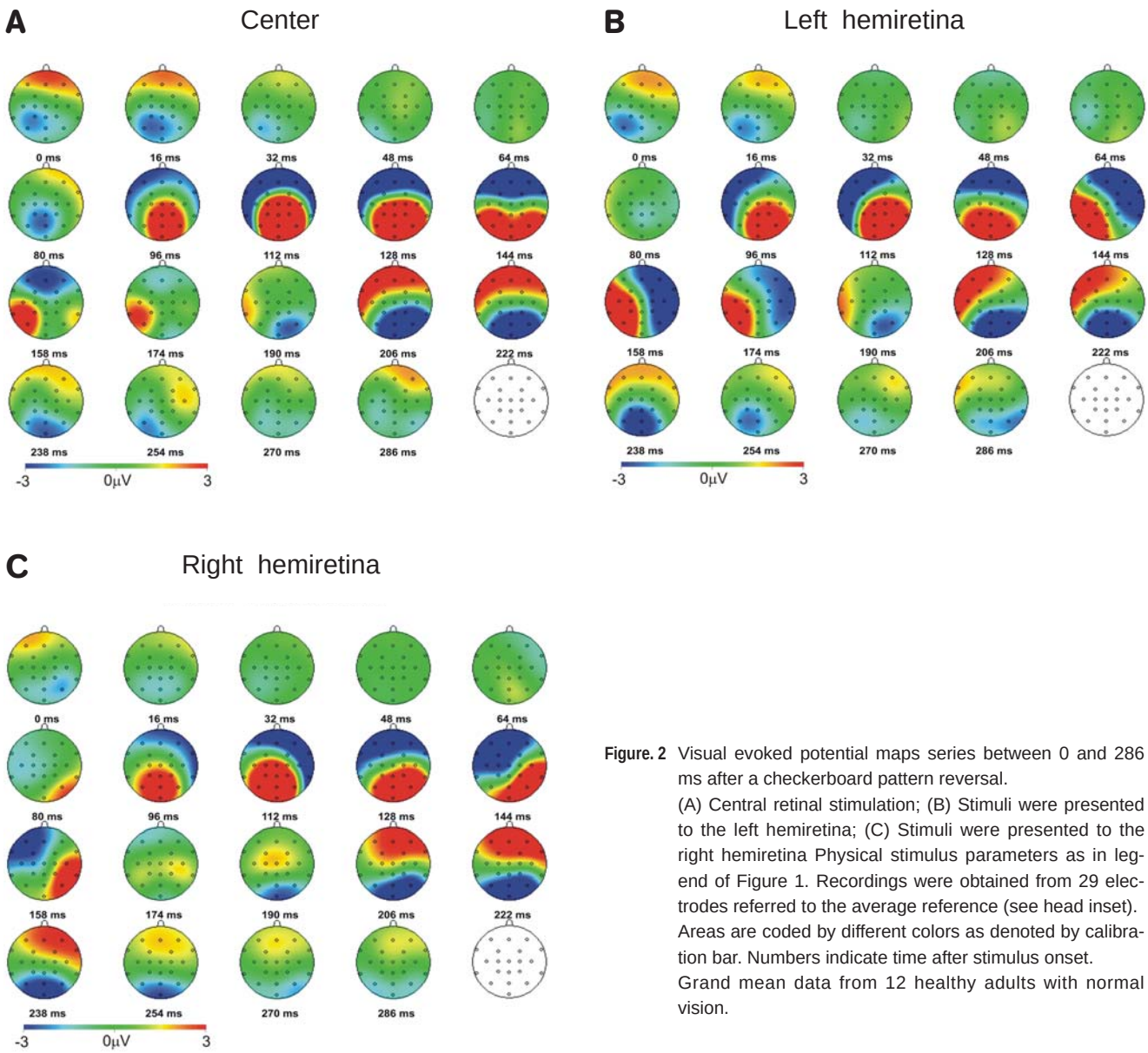

Figure. 2 Visual evoked potential maps series between 0 and 286 ms after a checkerboard pattern reversal.
(A) Central retinal stimulation; (B) Stimuli were presented to the left hemiretina; (C) Stimuli were presented to the right hemiretina Physical stimulus parameters as in legend of Figure 1. Recordings were obtained from 29 electrodes referred to the average reference (see head inset). Areas are coded by different colors as denoted by calibration bar. Numbers indicate time after stimulus onset.
Grand mean data from 12 healthy adults with normal vision.

instead of conventional time series (i.e., waveforms) at many recording points. It is obligatory that quantitative methods are applied to multichannel electrophysiological brain activity data in order to extract relevant information from such maps series in an objective way. In this section, methods for topographical data analysis will be illustrated, and it will be shown how field strength, component latency and topography can be used to quantify electrical brain activity.

Mapping of electrical brain activity in itself does not constitute an analysis of the recorded data but it is a prerequisite to unambiguously extract quantitative features of the scalp recorded electrical activity. In a second step, the derived topographical measures must be employed to statistically test differences between experimental conditions or between groups of subjects.

For the analysis of evoked brain activity one of the main goals is the identification of so-called components that are commonly interpreted as steps of information processing. In addition, it is mandatory that the data

space is reduced to a manageable size since multichannel recordings of electrical activity result in a large amount of data. The maps discussed above stem from 29 channels and were sampled at 500 samples/s over an epoch of 300 ms. This results in 4,350 individual amplitude values. It is self-evident that not each of these amplitude measures attains equal physiological importance, and as can be seen in the maps shown in Fig. 2, there occur potential field distributions with only very little activity (shallow gradients between 30 and 60 ms) while at other latency times the maps display high peaks and deep troughs with large potential gradients in the potential field distributions (at 112 or at 144 ms in Fig. 2).

From a physiological point of view it appears reasonable to define component latency as the occurrence time of maximal activity in the electrical field reflecting synchronous activation of a maximal number of intracranial neuronal elements. As a quantitative analysis tool to detect the amount of activity in a given scalp potential field we have proposed a measure of 'global field power' (GFP) that is computed as the mean of all possible potential differences in the field[11]. This corresponds to the standard deviation of all recording electrodes with respect to the average reference. Scalp potential fields with steep gradients and pronounced peaks and troughs result in a large GFP value, while global field power is small in potential fields with shallow gradients. Consequently, the maximum in a plot of global field power over time can be used to determine component latency. In a second step the features of the scalp potential field are analyzed at these component latencies. Global field power is a measure of the strength of activation at a given time point. For a quantitative assessment of topography, derived measures like location of potential maxima and minima or centers of gravity, and the steepness and orientation of gradients in the field can be employed. By definition these features independent of the reference electrode, and they will give an adequate description of the topography of electrical brain activity (see review by Lehmann and Skrandies[5]).

Global Field Power constitutes the spatial standard deviation of potential values within the electrode array (it is assumed that all values are measured against a common reference point). With a configuration of n electrodes on the scalp surface, the potentials e_i, i= 1, ..., n render the measured voltages $U_i = e_i - e_{common\ reference}$. For this potential distribution at a given time point, the reference-independent measure of GFP is computed as the mean of all potential differences within the field:

$$GFP = \sqrt{\frac{1}{2n^2}\sum_{i=1}^{n}\sum_{j=1}^{n}(U_i - U_j)^2} \qquad (1)$$

The computation of GFP considers all electrodes equally, and it corresponds to the root mean square amplitude deviations between all electrodes that are used to detect the electrical field of the brain. It is evident that this measure is not influenced by the choice of the reference electrode. Thus, it allows for a reference-independent treatment of the electrophysiological data obtained in topographic recordings.

For mapping, the use of the average reference is advantageous (see above), and GFP may be computed easily for EEG data referred to the average reference:

$$GFP = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(U_i - \frac{1}{n}\sum_{j=1}^{n}U_j\right)^2} \qquad (2)$$

We note that this mathematically equivalent to Formula (1).

Global Field Power computed according to Formulas 1 and 2 reflects the spatial standard deviation within each map at a given instant, and pronounced potential fields with large peaks and troughs and steep gradients are associated with large GFP values while with flat distributions GFP is small.

Field strength results in one number at each point of time, and in order to assess its dynamics it is plotted as a function of time. Such a display illustrates how field strength varies over time, and the occurrence of its maximum value in pre-determined time windows can used in order to identify brain activity components. Since all recording electrodes contribute equally to GFP the problems of conventional waveform analysis are avoided.

The GFP results belonging to the maps series discussed above are illustrated in Fig. 3 as a function of

time. Most prominent and consistent are three components that reach maximal field power between 78 and 82 ms (N80), between 108 and 112 ms (P100), and between 210 and 220 ms. With central visual stimulation brain activity is larger than when visual half-field stimuli are presented. For the P100 component this finding was highly significant in the subject population ($t=4.19$, $p<0.005$). The illustration is based on the mean of 12 subjects, and the analysis of the individual data yielded no significant difference of component latency when activity evoked by central, left, and right hemiretinal stimuli was compared.

We also note that periods of high global field power coincide stable potential field configurations where the spatial characteristics of the fields remain unchanged; in the present example a very similar potential field configuration is seen for the P100 component between 94 and 120 ms. Changes between components and topographical configurations occur rapidly and not as gradual transition. This supports the notion that evoked components can be interpreted as separate steps in information processing[11].

All of the measures derived from topographical maps sequences can be submitted to conventional statistical analysis and can be interpreted meaningfully in a physiological context: component latency may be equated with neural processing time, while field strength is an index of the amount of synchronous activation or the spatial extent of a neuronal population engaged in stimulus processing.

In order to quantify the topography of potential fields various measures can be used. One useful parameter for the definition of topographical characteristics constitutes the location of the centers of gravity (centroids) for the positive and negative area within each potential field. These locations consider the information of all recording points in a given map, and they constitute a sensible data reduction which can then be treated with statistical methods[12,13]. Differences in the topographical localization characterize the spatio-temporal distribution also over longer time epochs. Skrandies[14] illustrates how different aspects of visual information processing is reflected by sustained differences in topographical features. Visual stimuli of different spatial frequency yield significant differences in the activation of underlying neural assemblies that are selectively sensitive to different stimulus characteristics. Such effects are observed not only at the occurrence time of evoked components but may persist up to about 30 ms (for details consult Skrandies[14]).

Topographical features like centroid locations also allow for a segmentation of maps series into similar potential field configurations[5,13], and it has been demonstrated that these so-called "microstates" are different in healthy subjects and schizophrenic patients[15].

When topography is of interest, statistical analysis may also be performed on complete scalp distribution maps comparing data obtained in different experimental conditions or in different groups of subjects. The procedure is straightforward: statistical measures like t-value are computed for the data of each electrode. The results (either t-value or its significance) can then be plotted as a topographical distribution, and such a comparison of complete maps results in so-called significance probability maps (SPM)[5,16,17] that can be interpreted in terms of topographical differences induced by experimental variation.

STATISTICALLY DEFINED COMPONENTS

The computation and extraction of components

Digital human electroencephalographic data constitute multidimensional observations. Waveforms of evoked potentials have been analyzed by multivariate statistical methods since a long time[18-20]. This method is of even more interest when extensive multichannel data need to be analyzed, and statistical tools may be used for data reduction. Electrical brain activity can be considered as the sum of independent components, and Principal Component Analysis (PCA) can be employed to determine such underlying components.

The amplitudes of evoked potentials show some correlation between successive time points, and the signals obtained at neighboring electrode sites are also correlated. In addition to the autocorrelation inherent in evoked

potential data, variation of the independent experimental variables introduces systematic variation in the data set yielding patterns of correlation caused by stimulus or subject conditions.

Factor and principal components analysis constitute multivariate statistical analysis methods that are used in many different fields of research[21]. The primary aim of PCA is to find a reduced set of non-redundant descriptors that explain most of the variance in the original data. Principal components are by definition orthogonal, and their correlation is zero. After component extraction the loading pattern may be rotated to simple structure maintaining orthogonal relationships between components ("Varimax" rotation, see textbooks on multivariate statistics[21,22]). This procedure is used to maximize high component loadings and minimize low loading values, thus facilitating the interpretation of components.

In a second step, the contribution of each of the resulting components to the original data is determined by examining the component scores associated with experimental (or subject) conditions. These component scores are dependent measures like the recorded amplitude values, and experimental effects may be revealed by treating component scores with conventional statistical methods[21,23]. In addition, such a multivariate approach has proven useful when combined with dipole source modelling techniques[24].

Different from Factor Analysis, PCA does not consider unique factors that show high loadings only on individual variables[22]. This appears appropriate for our purpose, since, due to the autocorrelation in electrophysiological data mentioned above, neuronal activity modulated by experimental conditions never influences only single time points or isolated electrode positions. It also has been shown that a high percentage of the variance in a given data set is accounted for by only few principal components. This indicates that most of the variance of the recorded data is related to few common factors and unique factors can be neglected without much loss.

When evoked potential waveforms are analyzed by PCA, the amplitudes measured at successive time points are entered as variables while electrode positions, subjects and experimental conditions are the observations in the input data matrix. Topographical effects may then be analyzed by testing the statistical significance of the scalp distribution of component scores (i.e., gain factors assigned to different electrodes) obtained in different experimental or subject conditions. A topographical analysis of principal component scores has been successfully demonstrated on both one-dimensional potential profiles as well as on two-dimensional potential fields[6,19].

A different approach is employed for direct topographical analysis: a spatial PCA may be used in order to reduce the dimensionality of the data matrices where amplitudes at each electrode location constitute the variables, and time points, experimental conditions, or subjects are the observations. Here the correlation matrix (or covariance matrix) reflecting correlations between electrode locations is decomposed by PCA[23,25]. When waveforms are analyzed by PCA, then the resulting component loadings are basic waveforms. On the other hand, with topographical maps at input, the spatial PCA results in basic field configurations that reflect scalp distributions of component loadings.

The statistical method of PCA computation extracts components that are orthogonal, with the first principal component representing the maximum variation in the data, the second principal component is orthogonal to the first and represents the maximum variation of the residual data. This process of component extraction is repeated several times, and since the original variables are correlated only a small number of principal components accounts for a large proportion of the variance in the original data. When PCA is performed on multichannel evoked potential waveforms, typically between 6 and 10 principal components are found[6,19] while a spatial PCA results in about three or four basic field distributions that account for more than 90% of the variance[23,25,26].

A general linear model of topographical EEG or evoked potential maps can be written as

$$M(i) = S_1 \cdot C_1(i) + S_2 \cdot C_2(i) + ... + S_n \cdot C_n(i) + \overline{X} \qquad (3)$$

or in matrix notation:

$$M = S \cdot C' + \overline{X} \quad (4)$$

where M(*i*) is the potential map measured at i electrode sites, C_n are fundamental components (maps of component loadings, i.e. basic topographical distributions), S_n are component scores (gain factors) associated with subject or stimulus conditions, and $\overline{X}$ is the grandmean of the original data used as input for spatial PCA.

In this model the grandmean is added for only visualization of the results because the mean is removed from the original data when the covariance or correlation matrix is computed. In a similar way, the matrix M of (4) contains the original amplitude values, *C'* represents the component loadings, *S* the component scores, and $\overline{X}$ corresponds to the grandmean values.

Since principal components are extracted from the covariance or correlation matrix, the contribution of each component is relative to the grandmean of the original data. When the basic components derived from the correlation matrix shall be displayed as scalp distribution maps, the metric of each component should be restored to microvolt units by multiplying the component loadings by the respective standard deviations. In this way the units in the resulting maps are identical to those of the recorded data. This helps for understanding when the results are display graphically.

With the computation of spatial PCA, a large number of electrodes is reduced to few underlying components each of which is weighted by a score that indicates the contribution of each component to a given experimental or subject condition (see Formula 3). A more detailed description of the mathematical and statistical background of factor analysis and PCA can be found in the statistical literature[21,22]. There are also a few review papers and books on the application of PCA to biomedical signals[20,26,27].

Application of spatial principal components analysis

The extraction and definition of principal components is the first step of PCA, and in further analyses their relation to experimental conditions is of central interest. Conventional statistics like t-tests or analysis of variance using the component scores (gain factors) may reveal significant effects. In this section we will give an example of how spatial PCA can be used for data reduction and for the comparison of experimental conditions.

The complete data set part of which is presented in Fig. 2 was submitted to spatial PCA, and the results were

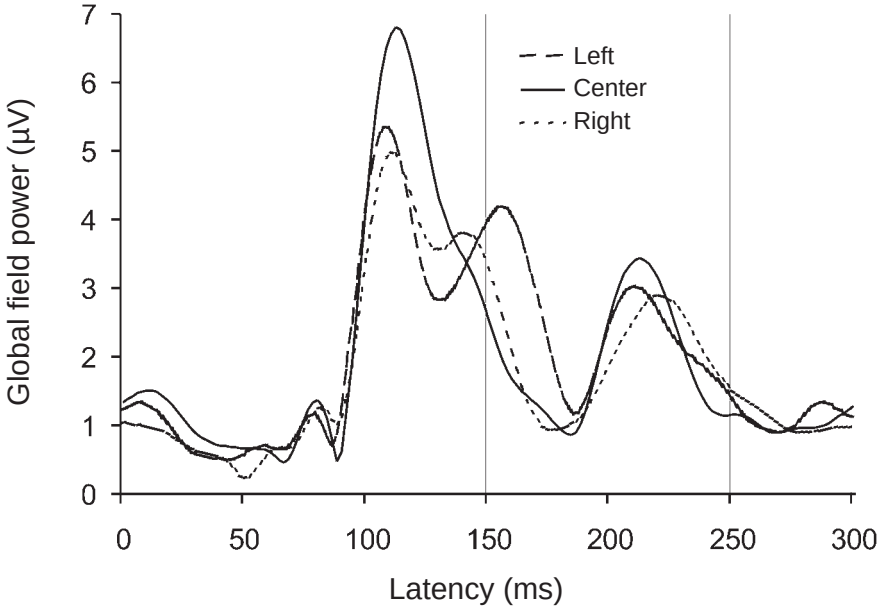

Figure 3. Global field power (GFP) as a function of poststimulus time computed on the data in shown in Figure 2 for stimuli presented in the center, or to the left or right hemiretina. Field strength displays maxima around 80 and 110 ms defining component latencies.

three topographical components with eigenvalues greater than 1.0 that accounted for 91.1% of the variance.

The topographical distribution of these principal components is displayed in Fig. 4. The first component explained 52.3% of the variance, and its main feature were distinct extreme values over the occipital areas. The second component accounted for 25.5% of the variance in the data, and it was characterized by a right occipital peak while the third component displayed a peak over the left occipital areas. This component still explained 13.3% of the variance. This appears as a meaningful numerical decomposition of the scalp field distributions. We note that not only this first component is important but that also components associated with less variance may carry useful information. This will be discussed in detail below.

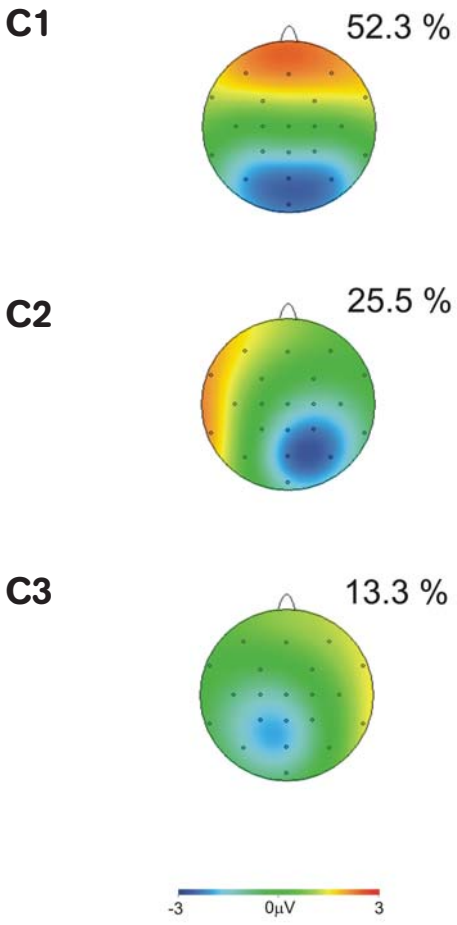

Figure. 4 Results of spatial PCA computed on the complete data sets illustrated in Figure 2. The maps illustrate the spatial distribution of three principal components (C1, C2, C3). These are basic field shapes with a component score of +1.0. The metric was restored to microvolt units by multiplying component loadings by their respective standard deviations. The numbers indicate the percentage that is explained by each of the components.
Areas are coded by different colors as denoted by calibration bar.

As a result of the spatial PCA the number of variables is reduced from 29 amplitude values at the electrodes to 3 component scores for each experimental condition and time point. Note that the polarity seen in the component distribution maps in Fig. 4 has no special meaning. For example, Component 1 shows an negativity over occipital areas when the associated component score is positive but the potential field polarity changes to occipital positive values when the scores are negative. This exactly what the general linear model of Formula 3 states.

The topographic pattern of principal components illustrated in Fig. 4 is very similar to the distribution of factor scores derived from frequency analyzes of spontaneous EEG or event-related activity. In a clinical study John et al.[28] have illustrated that the topographical distribution of scores on a limited number of factors may be used to successfully quantify the abnormality of patients with a wide variety of psychiatric disorders.

In the following we will exam how the spatial principal components are related to experimental conditions. As described above, Fig. 4 illustrates the topographical distribution of the basic spatial components, and the relation to the experiment may be revealed by analyzing the component scores associated with the original data. The scores are gain factors indicating the contribution of a given component to different experimental conditions. Fig. 5 displays the scores of Component 2 (Fig. 5A) and Component 3 (Fig. 5B) as a function of poststimulus time. The values are drastically different when activity elicited by left or right retinal stimuli is compared.

For stimuli on the left hemiretina, Component 2 has a score of -3.50 at 108 ms latency indicating that there is a dominant and large positivity over the right occipital areas. When right hemiretinal areas are stimulated, the

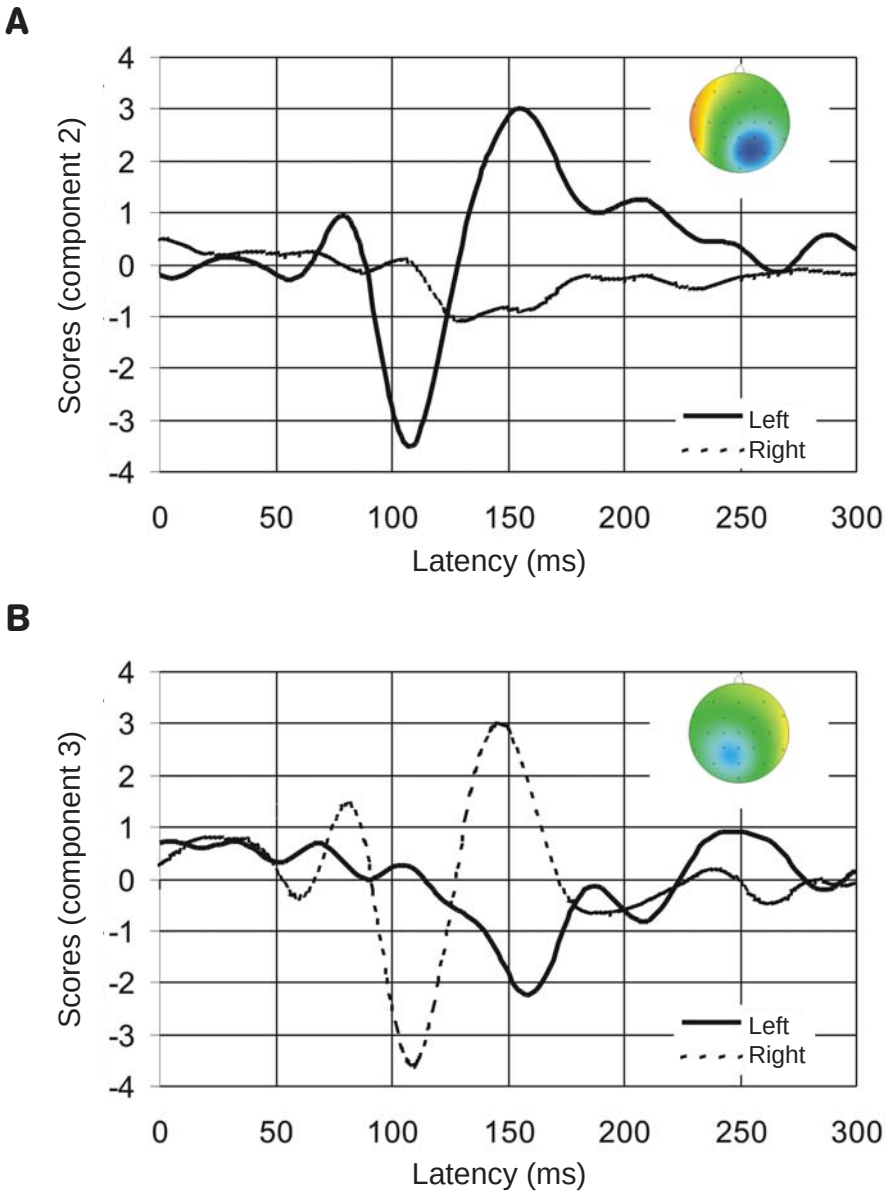

Figure. 5 Scores on Component 2 (A) and Component 3 (B) elicited pattern reversal stimuli presented to the left and right hemiretina as a function of time. Maps in insets display the basic topographical distribution of the components scaled by +1.0 (component score). It is obvious that the contribution of components depends on latency time and experimental condition.

contribution of this component is near zero (see Fig. 5A). Analysis of Component 3 reveals a different behavior: here left hemiretinal stimuli yield only very small component scores while at 108 ms latency stimuli presented to the right hemiretina result in a value of -3.59. This indicates that lateralization of a large positive component over the left hemisphere. In a similar way, the contribution of the components to the original data is very systematic and consistent when the latency range 140 and 160 ms is analyzed. Right retinal stimuli are followed by a large positive contribution of Component 3 (i.e., a score of 3.02 indicates that there is a strong negativity over right occipital areas) while left retinal stimuli are associated with high scores of Component 3 (i.e., a gain factor of 3.01 that stands for a negativity over the left occipital scalp regions). We note that with central stimuli the scores of these components are very similar (at 112 ms there is a score of -3.27 for Component 2 and a score of -3.11 for Component 3) indicating a positive distribution occurring simultaneously over the left and

right occipital scalp areas. Consequently, in this condition the left and right hemispheres are activated in a similar way. This illustrates that there is a straightforward functional interpretation of the spatial principal components detected in the statistical analysis: Component 2 stands for activity over the visual areas of the right hemisphere while there is an independent process (Component 3) that reflects lateralized electrical brain activity of the left hemisphere.

The physiological interpretation of principal components

Although there are meaningful results in the example illustrated above, the interpretation of PCA results needs some caution. For example, the general problem of the reference location that applies to the analysis of evoked potential waveforms (i.e., the change of waveforms with a change of the reference point) also pertains to time series analyzed by PCA. Changing the reference means to subtract a vector form the original data. Of course this linear change will cause alterations in the covariance and correlation matrix computed from the original amplitude measures. Since PCA reproduces the input matrix as a set of linear combinations any change of the original data caused by a different reference electrodes must also influence the derived solution, and PCA may not overcome problems with the input variables in the data set used for analysis.

It is also important to bear in mind that PCA results in statistically defined components. Thus, the interpretation of components derived from PCA computations must always consider that a specific principal component reflects a source of variance in the original data set. The pattern of component loadings depends on the covariation of potential amplitudes at various scalp locations over experimental conditions and recording time. The physiological or psychological interpretation rests on the experimental design of the study: Principal components are directly influenced by the variation in the recorded data set that is caused by experimental conditions. Thus, the spatial pattern of component loadings needs not necessarily represent physiological components, and the relation between principal components and physiological mechanisms must be demonstrated by the experimenter.

Although some statistical problems may arise when PCA is used carelessly for the analysis of EEG and evoked potential data[26,29], this method is able to reproduce underlying components with a high degree of accuracy. Spatial PCA is a powerful tool when used as a means of data reduction and for the detection of patterns of covariation in the multivariate data space. As obvious from Figs. 2, 4, and 5, many amplitude measures can be reduced to a very small set of components that are meaningfully related to experimental parameters. This has been repeatedly reported[6,18-20,25,28]. In a similar line, the finding that only three basic field distributions (i.e., underlying components) may explain more than 90% of the variance when data are analyzed over time is in good agreement with the results of segmentation studies that showed the reoccurrence of similar spatial patterns over time when evoked potential maps series were segmented by topographical criteria[14,30].

CONCLUSION

The data and results presented in this contribution illustrate that topographic mapping of brain electrical activity constitutes a very useful technique for the visualization of multichannel data in the form of electric scalp field distributions. In addition, this approach enables an adequate statistical and quantitative analysis of topographical electrophysiological recordings. The methods may be applied to brain activity that occurs spontaneously like EEG or is elicited by sensory stimulation or psychological events (EPs and ERPs). The measured electrical brain activity can be characterized in terms of latency (i.e., processing times), and amplitude which reflects synchronous involvement and extent of neuronal populations (i.e., field strength), and it is possible to delineate the topographical distribution of potential components that are further analyzed by conventional statistical methods like t-tests or analysis of variance.

For practical work, this approach of topographical analysis can be applied to studies on the functional states of the human brain, sensory and cognitive information

processing, and motor planning in healthy subjects. In addition, the topography of electrical brain activity is important for clinical questions on the intactness and functionality of the central nervous system of patients suspected of neurological or psychiatric disease. Such non-invasive experimental investigations are part of contemporary neurophysiological questions on how global states of the central nervous system affect brain functions such as processing of sensory or psychological information, movement planning and execution, or internal states related to cognition and emotion. In normal subjects and in patients these processes can be studied and characterized by spatio-temporal patterns of electrical brain activity with very high time resolution.

For clinical questions, sensory evoked brain activity is recorded in order to test and objectify the function the afferent pathways and central processing areas of various sensory modalities in patients with neurological, ophthalmological or audiological symptoms. On the other hand, event-related brain activity elicited during cognitive tasks has its main application in the fields of psychiatry and psychology where perception, cognition, attention, learning, or emotional processes are under study. All these research areas profit from the application of topographic mapping and analysis of brain electrical activity in real-time. One may reasonably predict that future applications of topographic mapping of electrophysiological activity will include the coregistration of the high time resolution EEG recordings with brain imaging methods like functional MRI. The interdisciplinary collaboration of these fields of research will lead to functional imaging of human brain activity with high temporal and high spatial resolution.

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