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Tiled Parallel Coordinates for the Visualization of Time-Varying Multichannel EEG Data

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Abstract

The field of visualization assists data interpretation in many areas, but some types of data are not manageable by existing visualization techniques. This holds in particular for time-varying multichannel EEG data. No existing technique can simultaneously visualize information from all channels in use and all time steps. To address this problem, a new visualization technique is presented, based on the parallel coordinate method and making use of a tiled organization. This tiled organization employs a two-dimensional row-column representation, rather than a one-dimensional arrangement in columns as used for the classical parallel coordinates. The usefulness of the new method, referred to as tiled parallel coordinates, is demonstrated by one particular type of EEG data. It can be applied to an arbitrary number of time steps, for the maximum number of channels currently in use. The general setup of the method makes it widely applicable to other time-varying multivariate data types.

Categories and Subject Descriptors (according to ACM CCS): E.0 [Data]: General; J.3 [Life and Medical Sciences]: Health

1. Introduction

Huge amounts of data are generated in many areas of research. Visualization techniques make this data more comprehensible. However, some types of data are not manageable by existing techniques. In particular, large quantities of time-varying multichannel electroencephalography (EEG) data are not well handled by current techniques. This paper presents a visualization technique capable of simultaneously displaying information from more time steps and more channels than existing techniques.

The problem to be solved bears some similarity to problems that can be handled by ThemeRiver, a well-known method capable of visualizing thematic variations over time across a collection of documents [HHN99]. However, some problems remain for the application of ThemeRiver to EEG data. On the one hand, we cannot objectively read "themes" from EEG data. On the other hand, even if we could define themes, a separate ThemeRiver plot would be necessary for every electrode.

One of the general methods currently used to visualize high-dimensional data sets, the parallel coordinate technique [ID90], makes use of N parallel axes for N-dimensional data vectors. The axes can be ordered arbitrarily and can display an arbitrary number of dimensions. However, as the number of data vectors becomes very large, the usefulness of the method decreases.

The new visualization technique for time-varying multichannel EEG data, referred to as tiled parallel coordinates, is based on the parallel coordinate method and additionally employs a two-dimensional tiled layout. Some aspects of both techniques have already been used in different ways to visualize EEG data properties. First, the 'parallel coordinate' principle has been used to display time-voltage information, without explicitly mentioning it [RJJG*97]. Second, a tiled layout using a two-dimensional row-column arrangement, as opposed to the one-dimensional arrangement in columns for parallel coordinates, has been used for the visualization of time-frequency information from the EEG [GHLP02]. However, the new technique shows latency and amplitude information from the EEG instead. Moreover, the combination of the tiled layout technique with parallel coordinates

also makes information available across tiles, in contrast with [GHLP02].

The usefulness of the new method is demonstrated using one specific type of EEG data, so-called somatosensory evoked potentials (SEPs). It has advantages over existing EEG visualization techniques, in the sense that the largest number of channels currently in use can be handled for arbitrary amounts of time steps.

The general setup of the method makes it widely applicable to other time-varying multivariate data types.

2. EEG visualization

Several visualization techniques are already used in the field of EEG. Before we discuss the most important ones, we first present some relevant characteristics of EEG data.

2.1. Characteristics of EEG data

During an EEG experiment, the electrical activity of the brain is measured using electrodes attached to the scalp at different locations. These electrodes, which number up to 256 in current practice, are often held in fixed positions by an elastic cap.

From all electrodes simultaneously, an electrical potential is measured at sampling rates up to 2000 Hz. A clinical experiment takes about 15 to 30 minutes, whereas some scientific experiments can go on for hours (e.g. sleep experiments). During the experiments, stimuli (e.g. light flashes) can be presented to the subject in order to evoke specific brain responses (evoked potentials).

The measured signal from each electrode is amplified, resulting in one channel for every electrode. If many electrodes are used (e.g. 64 or 128), the term 'multichannel' or 'high-density' EEG is used.

An excellent overview on EEG is given by Niedermeyer & Lopes da Silva [NLdS87].

2.2. Existing EEG visualization techniques

For EEG data, basically only a few visualization techniques are in use. In principle, many more different features could be extracted from the same EEG data set and could be used for visualization. Occasionally, combinations of two visualization techniques are employed.

2.2.1. The conventional EEG representation

The conventional EEG representation consists of a collection of simple graphs, with time set out horizontally and the measured voltage vertically. Per electrode, one graph is drawn (fig. 1). It is also possible to plot graphs for the voltage difference between two electrodes.

A limited number of these graphs can be shown on a single screen, to be inspected by a clinician for the presence of certain phenomena. Several different orderings of the graphs can be employed ("montages" in EEG terminology). To study more graphs than visible on the screen, vertical scrolling is necessary.

Each graph commonly displays a time interval up to 10 s. To inspect the EEG data, a clinician typically scrolls horizontally from one marked event to the next.

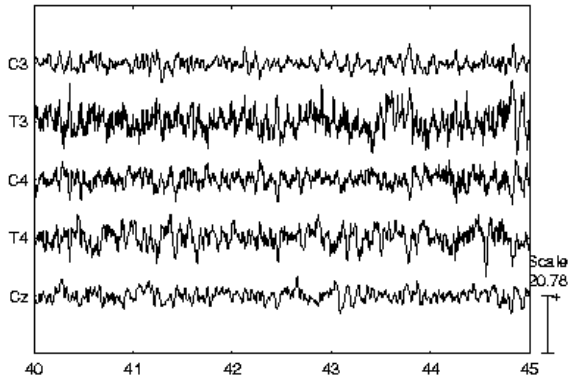

Figure 1: *Conventional EEG representation. Measured voltages for a five second time interval are shown, for five electrodes (indicated by the labels C3, T3, C4, T4, and Cz).*

2.2.2. Butterfly plot

Butterfly plots employ an organization of the data similar to the conventional EEG representation, except that the signals for all electrodes are superimposed (fig. 2). Butterfly plots can be used in analyses of multichannel evoked potentials. In the plots, those moments in time stand out at which the majority of the potentials have either a very large or a very small amplitude. Due to the resulting clutter, single channels cannot be identified any longer.

2.2.3. Topographic layout

Topographic layouts make use of the known electrode locations to display the voltages on a head shape. The voltages can be extracted from one time step in a topographic map, or multiple time steps in a topographic array.

Generally, topographic layouts are perceived more naturally than other layouts.

Topographic map

A topographic map displays information about the measured potential at all electrodes for a single time step. This information is color-coded and mapped to the corresponding electrode position on the scalp (fig. 3). The voltage values are spatially interpolated and mapped to corresponding colors. Sometimes isolines are included. A limited number of topographic maps can be explored simultaneously.

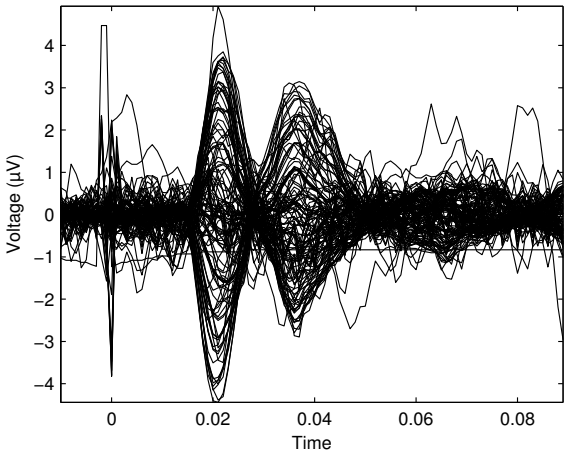

Figure 2: *Butterfly plot, showing 0.1 s of data, for 128 electrodes.*

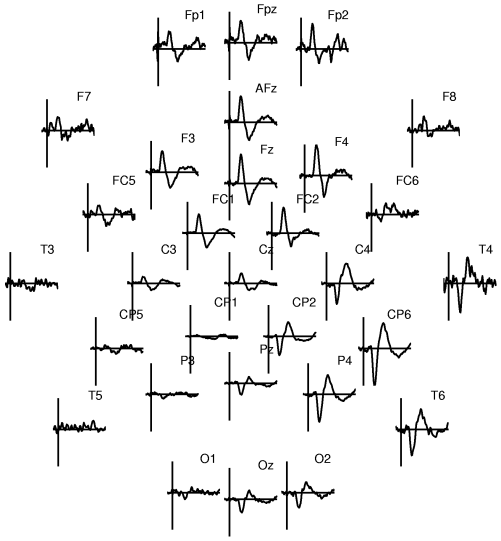

Figure 4: *Topographic array, for thirty electrodes.*

It is not evident which color scale should be employed. One reason is that the scale is sensitive to electrode signals containing large-amplitude noise. Also, human perception lacks a natural sense for multicolor scales. Even when a monocolor scale is used, misleading perceptions can be invoked by the areas surrounding the region of interest [Tuf90, War00].

Figure 3: *Topographic maps, for four consecutive time steps, including isolines. (See also color insert.)*

Topographic array

To create a topographic array, the conventional EEG representation is displayed at the positions of the electrodes. Usually, approximately one second of data and up to thirty graphs are visualized (fig. 4). Including more than this number of graphs results in a cluttered view. In general, it is difficult to compare two graphs located at different positions.

2.2.4. ERP image

To obtain an event related potential (ERP), a series of stimuli is offered during an EEG experiment (e.g. sound beeps). For every single stimulus the EEG response is measured. After acquiring the responses to many identical stimuli, an average response is calculated, called the ERP [JMW*01].

Generally, if two stimuli are identical, then two nearly identical responses are expected. However, from trial to trial responses may differ. To gain insight in the differences between individual responses, an ERP image displays multiple responses recorded at a single electrode in a single image [JMW*01], see figure 5. The responses can be put in any desired order, and consecutive responses are usually averaged. Such averaging, used to smoothen the image, obscures cases in which a response deviates occasionally from other responses.

To observe differences between responses recorded at two separate electrodes, several ERP images can be produced. A procedure to plot ERP images is available in EEGLAB, an open source Matlab toolbox for analyzing EEG [DM04].

3. Tiled parallel coordinates for time-varying multichannel EEG data

To visualize multichannel EEG data, our new technique is presented here, based on the combination of parallel coordinates with a tile-wise organization. Such an organization using tiles has been used before to visualize frequency information from the EEG [GHLP02]. However, the new technique shows latency and amplitude information from the EEG instead. Moreover, the combination of the tiled layout technique with parallel coordinates also makes information available across tiles, in contrast with [GHLP02].

A specific type of EEG data is used to illustrate the new technique. It concerns a somatosensory evoked potential (SEP), obtained by electrical stimulation of the median nerve (near the wrist of a subject). The average over approximately 500 stimuli is called a SEP. For a SEP, mainly contralateral brain activity is expected.

From now on, the EEG data recorded from N electrodes

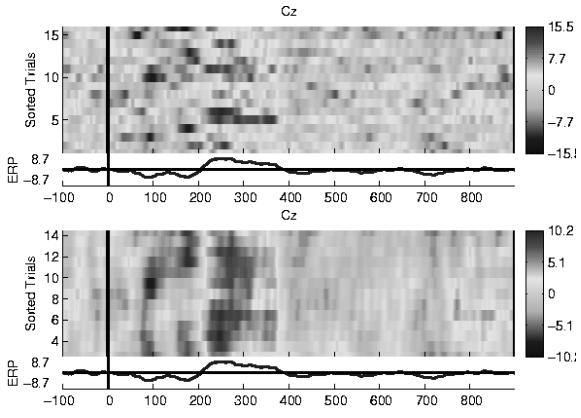

Figure 5: *ERP images.* Top: *ERP image without smoothing. Sixteen responses are color-coded separately.* Bottom: *Smoothened image. The average of three consecutive responses is color-coded. Below both ERP images, the (average) ERP is shown. (See also color insert.)*

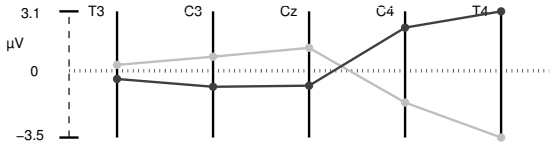

Figure 6: *Parallel coordinate representation for two five-dimensional vectors, each of which represents one time step. For each vector, one connected line is drawn. The data have been recorded from five EEG electrodes simultaneously (labeled T3, C3, Cz, C4, and T4). The voltage (μV) is set out vertically.*

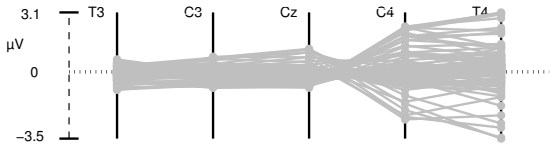

Figure 7: *Parallel coordinate representation for a hundred time steps and the same number of electrodes as in figure 6.*

simultaneously is represented by one N-dimensional vector per time step. Each vector element corresponds to a potential measured at one time-step at one electrode.

3.1. Review of the parallel coordinate method

The parallel coordinate method [ID90] shows each data dimension as a (usually) vertical axis. For N-dimensional vectors, N uniformly spaced parallel axes are used; they can be put in any desired order. To display a single vector, each vector element is indicated by a dot at the corresponding vertical axis, where all dots for a single vector are connected by a single line (fig. 6).

Two features can be left out of a parallel coordinate visualization, without loss of information. First, the axes do not need to be drawn [Tuf83]. Second, the connected lines do not always contribute extra information, so they can be omitted as well; in that case, data vectors can be distinguished by using different icons or colors. On the other hand, it requires less effort to study the difference between the data vectors if connected lines are shown.

Extra information can be added to the parallel coordinates via a special design of the axes [YWRH03]. Other techniques similar to parallel coordinates are circular coordinates [WLG97] and extruded parallel coordinates [LMP03]. The circular coordinates organize the axes as spokes in a wheel. The extruded parallel coordinates are organized as a two-dimensional plane in three-dimensional space; in three-dimensional space, occlusions are inevitable. A few other techniques are dedicated to cluster visualization based on parallel coordinates [FWR99], but it is not our current aim to find clusters in EEG data.

Various online sources offer possibilities to use parallel coordinates for visualizing data, such as GGobi (`http://www.ggobi.org`) and XmdvTool (`http://davis.wpi.edu/~xmdv`).

3.2. Tile design

The new visualization technique displays EEG data features on tiles (one tile for each electrode). These EEG data features are derived from the amplitude distribution per electrode.

3.2.1. Minmax plot

For every tile corresponding to one of the electrodes, the minimum and maximum is displayed (fig. 8). This plot is referred to as a 'minmax plot'. In the minmax plot, the white area on a tile displays a quantity. This has some resemblance to a mosaic display, using a space-filling design composed of tiles to show values in contingency tables [Fri02]. However, the design of the mosaic display allows both the total tile size and the tile position to be changed, in contrast with the minmax plot. Besides, the white area on a tile of the minmax plot depends solely on one quantity (the maximum difference in the measured potentials) instead of two, similar to the area of a bar in a bar chart.

3.2.2. Density map

For a limited number of data vectors, parallel coordinates can show the distribution of the data per axis. To maintain insight in the data distribution for very large numbers of data vectors, histograms can be superimposed on the vertical axes [HLD02], or histograms can be plotted separately beneath the axes [SYSH03].

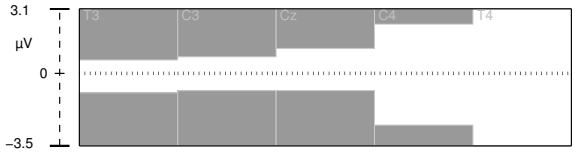

Figure 8: *Minmax plot containing five tiles, showing the extreme values for five electrodes. For the 100 data vectors shown in figure 7, the intervals containing no vector elements are excluded. The amplitude scale is indicated with a dashed line on the left, while the zero-level is indicated with a dotted line.*

Alternatively, the histogram is coded with grey scale values, resulting in a more intuitive density map (fig. 9). Here, the grey value indicates the local density of the vector elements, with dark grey representing a high and white a low density. Depending on the data characteristics, inverted grey scales or color scales can be employed.

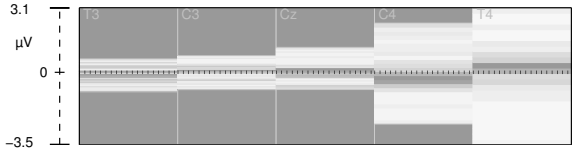

Figure 9: *Density map, combined with minmax plot, for the data in figure 7, reflecting the distribution of the vector elements along the vertical axes (dark grey for high, light grey for low densities).*

3.2.3. Combination of parallel coordinates, minmax plot and density map

The features represented by the minmax plot and the density map can be used as context features in a parallel coordinate data representation (fig. 10). For a connected line corresponding to a particular moment in time, one can observe whether a measured value occurred frequently at a channel (if the connected line crosses a dark grey region), or rarely (if the connected line crosses a light region).

For the example in figure 10, a separate routine was used to find the time-steps to be represented by parallel coordinates. This routine looks for local maxima in the global field power (GFP), which is a measure for the overall variation in the potentials. Large variations are associated with large changes in brain activity and are therefore assumed to be clinically relevant.

3.3. Tiled parallel coordinates

Instead of a one-dimensional arrangement of the tiles (in columns), they can also be organized in a two-dimensional

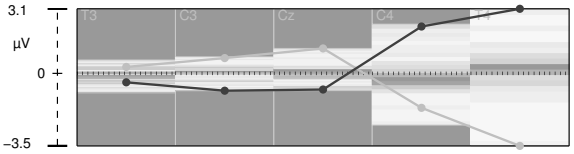

Figure 10: *Combination of parallel coordinates, the minmax plot, and the density map.*

row-column representation. As each tile represents one electrode, the tiles are displayed at corresponding positions on a head shape. We refer to this as a tiled parallel coordinate (TPC) map. Note that the physical position of the electrodes does not correspond exactly to a regular grid, causing some tiles to be empty.

Two TPC maps are shown in figure 11, one for left-hand and one for right-hand stimulation. For both stimulations, two time instants are indicated with red and blue lines, respectively. Although there is an overall voltage difference, we can make a few clear observations. First, the large amplitudes are mainly found on the contralateral side. Second, per TPC map, many electrodes show contrasting amplitudes for the two selected time instants (red minima in combination with blue maxima, and vice versa). Third, comparing the left-hand to the right-hand SEP, the extreme values caught by the colored lines for left-hand stimulation have correspondingly colored extreme values on the contralateral side for the right-hand SEP. Finally, the correspondingly colored lines for both sides occur around the same time instants: for the red line, 0.021 ms left versus 0.022 ms right; for the blue line, 0.036 ms left versus 0.041 ms right.

Altogether, as expected for a healthy person, a clear mirror symmetry is observed between the two TPC maps. For patients with a certain type of neurodegenerative disease, this mirror symmetry may be distorted, which makes this visualization technique potentially useful for clinical application.

A TPC plot displaying information from 116 channels is demonstrated in figure 12.

4. Evaluation

To evaluate all EEG visualization methods mentioned in this paper, we present an overview of scores for four criteria. First of all, the number of time steps that can be visualized is indicated. Second, we display to which extent the time order is explicitly visible. Third, the number of electrodes that can be properly analyzed is indicated. Finally, we express whether or not the spatial order of the electrodes is preserved. In table 1, the scores for all visualization methods are summarized. Scores have been assigned qualitatively and are indicated by black dots, ranging from no dots for the lowest score to three dots for the highest one.

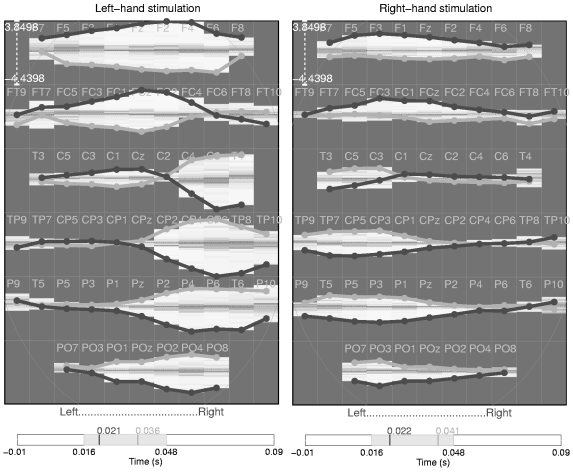

Figure 11: *Two TPC maps, both offering a top view of 58 electrodes (nose on top) and showing EEG data for a left-hand and a right-hand SEP, respectively. Each tile corresponds to one electrode. The red and blue lines correspond to two time steps. In the plot below, linked brushing of points indicates the corresponding instants on the time axis. (See also color insert.)*

We observe that the tiled parallel coordinate visualization technique can display the most time steps. The density maps together with the minmax plot can in fact include information for an arbitrary number of time steps. However, the TPC technique has lost an explicit time order, although some chronological ordering is preserved in the linked view by showing the corresponding instants on a time axis.

Concerning the visualization of the electrode locations, methods b, c, and g can incorporate the maximum number of electrodes currently in use. Clearly, the topographical techniques c, d, and g best preserve the explicit electrode ordering.

5. Conclusions and future work

In this paper, we surveyed existing visualization techniques used for EEG data and proposed a new technique, tiled parallel coordinate (TPC) maps, to visualize time-varying multichannel EEG data. The new method combines parallel coordinates with a two-dimensional tile-wise arrangement. Density maps in combination with minmax plots display contextual information, while parallel coordinates provide a focus on time instants of special interest. These special instants are found by a separate routine, which looks for the moments with maximal variation of the electrode potentials.

The new technique can handle more electrodes and more time steps simultaneously than existing EEG visualization techniques. Although it has lost an explicit time order, some chronological ordering is still preserved by using a linked

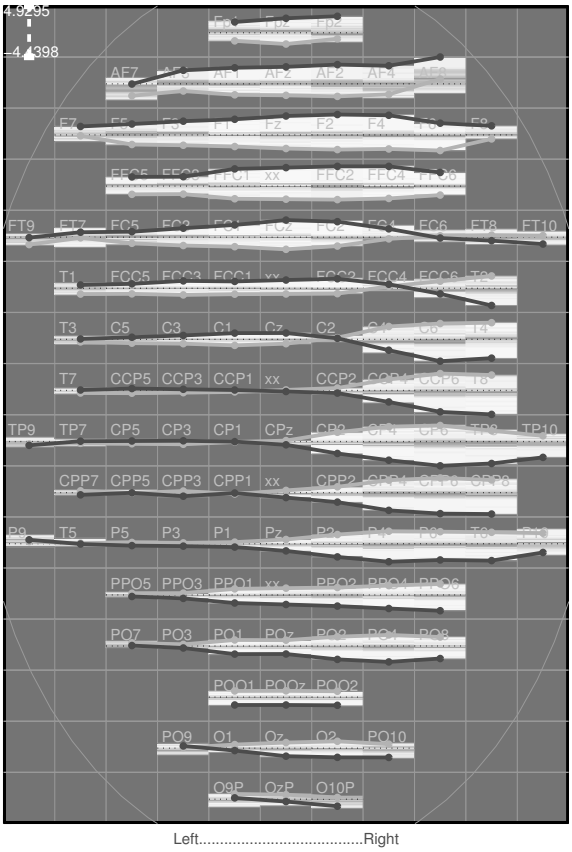

Figure 12: *TPC map for left-hand stimulation showing 116 channels. The same data set has been used again and the same time-steps are shown with connected lines as in figure 11. Locations where no electrodes were attached have been marked as 'xx'. For each time-step, these have been assigned the averaged value over their neighbors.*

view showing the corresponding time instants on a time axis. The two-dimensional topographic organization of the tiles corresponding to the electrode locations results in a more natural ordering of the dimensions than is possible with conventional parallel coordinates. Whereas on the one hand the visualization technique is sensitive to electrode signals containing large-amplitude noise, it on the other hand offers the opportunity to immediately identify exactly those electrodes recording much noise.

For the case of bilateral SEPs, a clear mirror symmetry will be visible between the corresponding TPC maps for healthy persons. For patients with a certain type of neurodegenerative disease, this mirror symmetry may be distorted, which makes this visualization technique potentially useful for clinical application.

We already presented our new visualization technique to

Table 1: *Scores for all EEG visualization methods considered in this paper. For the meaning of the dots for the number of time steps and the number of channels, see bottom. In the columns referring to order, the number of dots (ranging from zero to two) indicates to which extent an explicit time order or spatial ordering of the electrodes, respectively, is employed.*

	Methods	Time		Channels	
		No.	Order	No.	Order
a	convent. EEG	●●	●●	●●	●
b	butterfly plot	●●	●●	●●●	
c	topogr. map	●●	●	●●●	●●
d	topogr. array	●●	●●	●●	●●
e	ERP image	●●	●●	●●	●
f	par. coord.	●●		●●	●
g	tiled par. coord.	●●●	●	●●●	●●

Time/No. : ● 1; ●● ∼1,000; ●●● ∼100,000.
Channels/No. : ● 1; ●● 1-30; ●●● 30-128.

clinical EEG experts. A clinical evaluation is planned for the near future, in which the TPC method will be compared to an existing EEG review technique.

Like many other methods, the TPC technique is designed to display time-voltage information from separate time instants. In addition, several frequency analysis techniques are currently employed. Consequently, we will soon also explore time-frequency visualization techniques for EEG data.

Although our new method was developed in the area of EEG data visualization, it is potentially useful for arbitrary time-varying multivariate data types.

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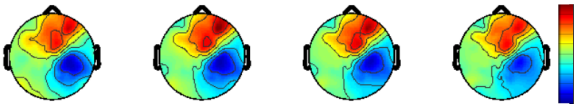

Figure 13: *Topographic maps, for four consecutive time steps, including isolines.*

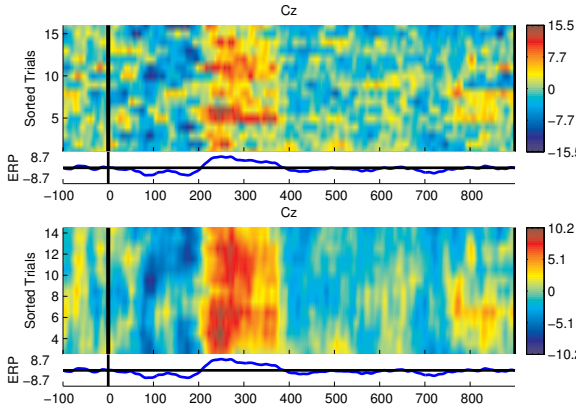

Figure 14: *ERP images.* Top: *ERP image without smoothing. Sixteen responses are color-coded separately.* Bottom: *Smoothened image. The average of three consecutive responses is color-coded. Below both ERP images, the (average) ERP is shown.*

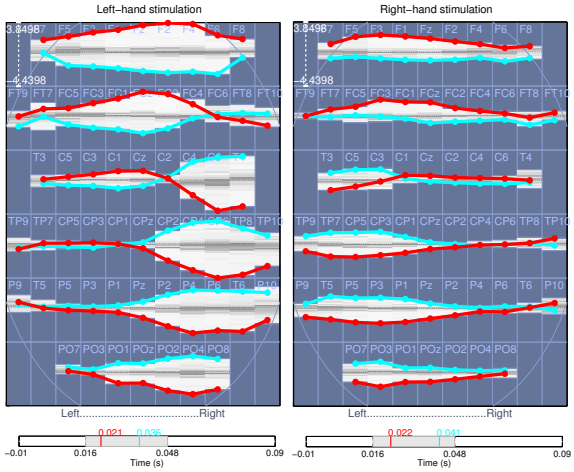

Figure 15: *Two TPC maps, both offering a top view of 58 electrodes (nose on top) and showing EEG data for a left-hand and a right-hand SEP, respectively. Each tile corresponds to one electrode. The red and blue lines correspond to two time steps. In the plot below, linked brushing of points indicates the corresponding instants on the time axis.*