Design and Evaluation of Tiled Parallel Coordinate Visualization of Multichannel EEG Data

Michael ten Caat[(a,b)], Natasha M. Maurits[(b,c)], and Jos B. T. M. Roerdink[(a,b)], *Senior Member, IEEE*

***Abstract*— The field of visualization assists data interpretation in many areas, but does not manage all types of data equally well. This holds in particular for time-varying multichannel EEG data. No existing method can successfully visualize simultaneous information from all channels in use at all time steps. To address this problem, a new visualization method 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 classical parallel coordinates. The usefulness of the new method, referred to as tiled parallel coordinates (TPC), is demonstrated by a particular type of EEG data. It can be applied to an arbitrary number of time steps, handling the maximum number of channels currently in use. An extensive user evaluation shows that, for a typical EEG assessment task, data evaluation by the TPC method is faster than by an existing clinical EEG visualization method, without loss of information. The generality of the TPC method makes it widely applicable to other time-varying multivariate data types.**

***Index Terms*— Information visualization, multivariate visualization, time-varying data, electroencephalography (EEG), user evaluation.**

I. Introduction

HUGE amounts of data are generated in many areas of research. Visualization methods can be used to make these data more comprehensible. However, some types of data are not manageable by existing methods. In particular, large quantities of time-varying multichannel electroencephalography (EEG) data are not well handled by current methods. This paper presents a visualization method capable of simultaneously displaying information from more time steps and more channels than existing methods. Following up on our earlier work [1], we also present the results of a user evaluation of the method.

One of the general methods currently used to visualize high-dimensional data sets, the parallel coordinate technique [2], makes use of N parallel axes for N-dimensional data vectors. The axes can be ordered arbitrarily and an arbitrary number of dimensions can be displayed. However, as the number of data vectors becomes very large, the usefulness of the method decreases.

Our new visualization method for time-varying multichannel EEG data is referred to as tiled parallel coordinates (TPC). The TPC method is based on two principles that already have been used separately for EEG data. The first is the 'parallel coordinate' principle, which has been used to display time-voltage information, although the principle is not explicitly mentioned [3]. The second principle is a tiled layout, using a two-dimensional row-column arrangement, which is an extension of the usual one-dimensional arrangement in columns for parallel coordinates. The tiled layout has been used for EEG data to visualize time-frequency information [4]. However, the TPC method visualizes latency and amplitude information instead. Moreover, the TPC method combines the tiled layout with parallel coordinates, making information available across tiles.

The usefulness of the new method is demonstrated for one specific type of EEG data, somatosensory evoked potentials (SEPs). Students, researchers, and clinicians performed a task with typical SEP assessment elements in an extensive user evaluation.

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The authors are with: (a) Institute for Mathematics and Computing Science, University of Groningen, P.O. Box 800, 9700 AV Groningen, The Netherlands; (b) BCN Neuroimaging Center, University of Groningen, The Netherlands; (c) Department of Neurology, University Medical Center Groningen, The Netherlands. E-mail: mtc@cs.rug.nl.

II. EEG Data

Before we show existing EEG visualization methods, we first present relevant properties of EEG data.

A. Characteristics

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. Each electrode carries a unique labeling by a combination of letters and digits (e.g. F3, Cz, P4, as in Fig. 4).

From all electrodes simultaneously, the 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 a specific brain response, the so-called evoked potential (EP).

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

An excellent overview of the EEG technique is given by Niedermeyer & Lopes da Silva [5].

B. Somatosensory Evoked Potential (SEP) Data

To illustrate the new method and some basic EEG visualization methods, we will use the somatosensory evoked potential (SEP), obtained by electrical stimulation of a nerve [6]; in our case, this is the median nerve (near the wrist of a subject). The average EEG over approximately 500 electrical stimuli is called a SEP (Fig. 1). For a SEP, contralateral brain activity is expected: for left median nerve stimulation, the response is expected mainly in the right hemisphere, and vice versa. Positive and negative peaks are identified in the SEP with their amplitudes and latencies; these are called SEP *components* (Fig. 1).

III. Existing EEG Visualization Methods

A. Conventional EEG Representation

The conventional EEG representation consists 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 or researcher for the presence of certain phenomena. Commonly, each graph 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.

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.

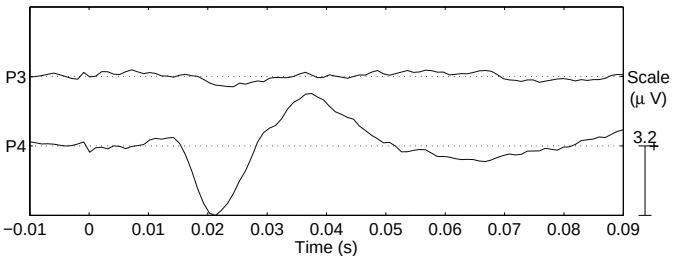

Fig. 1. Conventional EEG representation for two electrodes, labeled P3 and P4 (SEP, left median nerve stimulation). The dotted line indicates the zero-level. The first negative peak for P4, just after 20 ms, is referred to as the N20 component, or 'N20' for short.

B. 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, specific 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.

C. 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.

1) Topographic Map: This 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

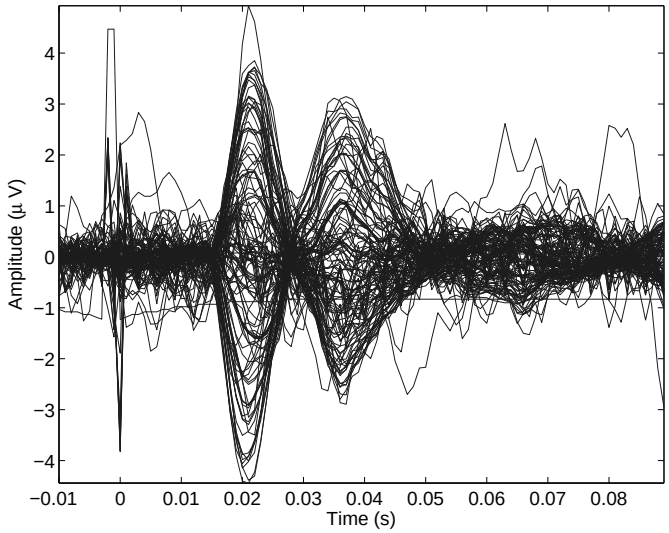

Fig. 2. Butterfly plot, showing 100 ms of SEP data, for 128 electrodes.

number of topographic maps can be explored simultaneously.

It is not obvious which color scale should be employed. One reason is that the scale is sensitive to electrode signals containing large-amplitude noise. Another reason is that human perception lacks a natural sense for e.g. a rainbow scale [7, p. 92]. Furthermore, contextual effects can cause misleading perceptions; contrast can be visually increased between similarly sized adjacent regions, or contrast can be visually decreased between a large and a small neighboring region. This is referred to as 'simultaneous contrast' and 'assimilation', respectively [8], [9].

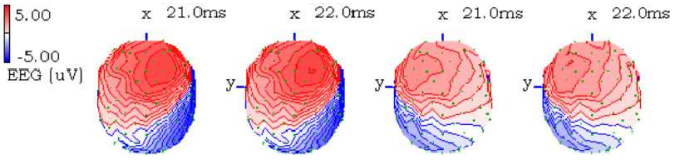

Fig. 3. Four topographic maps, including isolines (top view, nose on top). Notice the mirror-symmetry between the two on the left (21 and 22 ms after left median nerve stimulation) and the two on the right (21 and 22 ms after right median nerve stimulation).

2) 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 visually compare two graphs located at different positions.

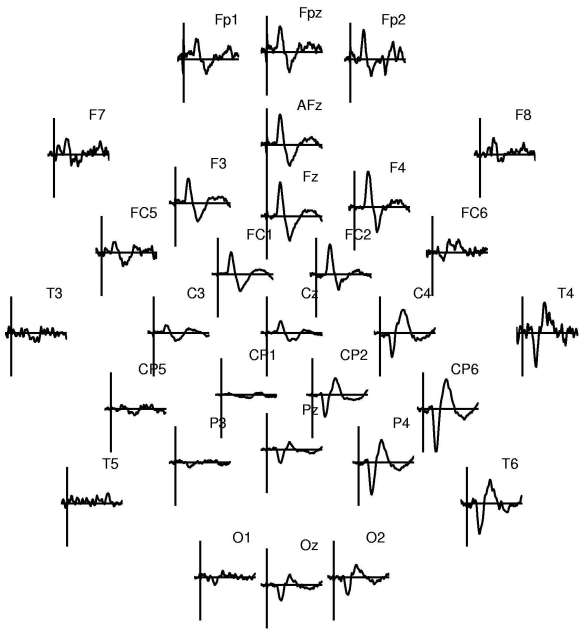

Fig. 4. Topographic array, for left median nerve stimulation and thirty electrodes. Top view, nose on top.

D. EP Image

Generally, if two stimuli used to generate an EP are identical, then two nearly identical responses are expected. However, from trial to trial responses may differ. To gain insight in the variability between individual responses, an EP image displays multiple responses recorded at a single electrode in a single image (Fig. 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 compare responses recorded at two separate electrodes, several EP images can be produced. A procedure to plot EP images is available in EEGLAB, an open source Matlab toolbox for analyzing EEG data [10]. The EP image is also referred to as ERP (event-related potential) image [11].

IV. Tiled Parallel Coordinates for Multichannel EEG Data

We now present our new method for visualizing multichannel EEG data, based on the combination of parallel coordinates with a tile-wise organization. EEG data recorded from N electrodes simultaneously are represented by one N-dimensional vector per time step. Each vector element corresponds to a potential measured at one time-step at one electrode.

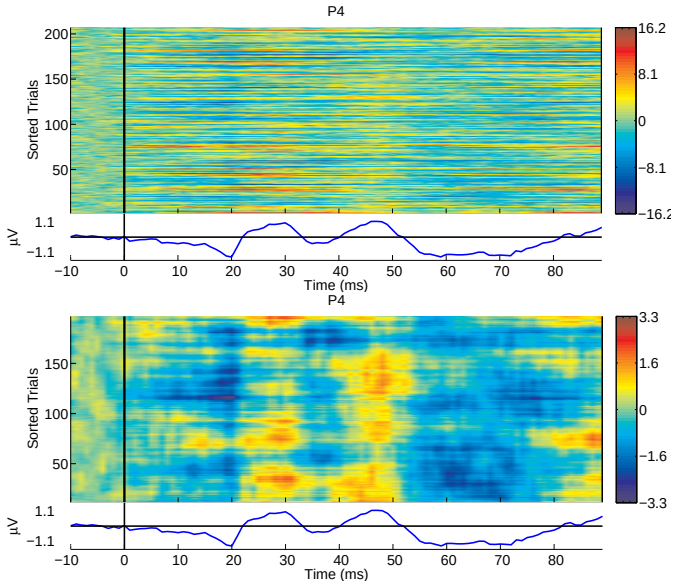

Fig. 5. EP images for the electrode labeled P4 (SEP, left median nerve stimulation). *Top:* EP image without smoothing; 207 responses are color-coded separately. *Bottom:* Smoothened image. The average of twenty consecutive responses is color-coded. Below both EP images, the average EP is shown.

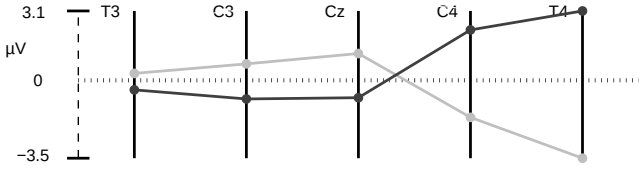

Fig. 6. Parallel coordinate representation for two five-dimensional vectors, each of which represents one time step. For each vector, one polyline is drawn. The data have been recorded from five EEG electrodes simultaneously (labeled T3, C3, Cz, C4, and T4). The voltage (μV) is set out vertically.

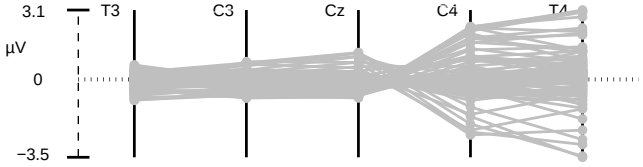

Fig. 7. Parallel coordinate representation for 100 time steps and the same number of electrodes as in Fig. 6.

A. Review of the Parallel Coordinate Method

The parallel coordinate method [2] shows each data dimension as a (usually) vertical axis. For an N-dimensional vector $(x_1, x_2, ..., x_N)$, N uniformly spaced parallel axes are used; these axes can theoretically be put in any desired order, but in practice the ordering might affect the data analysis. To display a single vector, each vector element is indicated by a dot at the corresponding vertical axis, and all dots for a single vector are connected by a single polyline (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 [12, p. 129]. Second, the polylines 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 polylines are shown.

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`).

Extra information can be added via a special design of the axes [13]. Other methods similar to parallel coordinates are circular coordinates [14], which are referred to as star glyphs in XmdvTool, and extruded parallel coordinates [15]. 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 methods are dedicated to cluster visualization based on parallel coordinate plots [16], [17]. However it is not our current aim to find clusters in EEG data.

B. Tile Design

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

1) Minmax Plot: For every electrode, there is one tile. A minmax plot displays the minimum and maximum per tile (Fig. 8). As the white area on a tile displays a quantity, it has some resemblance to a mosaic display [18], which allows the tile height, width, and position to be varied. In contrast, the minmax plot only has a variable height. We have not normalized tile sizes, but used a single scale for all tiles (see the top left tile, Fig. 8). This simplifies comparisons between tiles.

2) Density Map: Parallel coordinates can show the distribution of the data per axis for a limited number of data vectors. To maintain insight in the data distribution for very large numbers of data

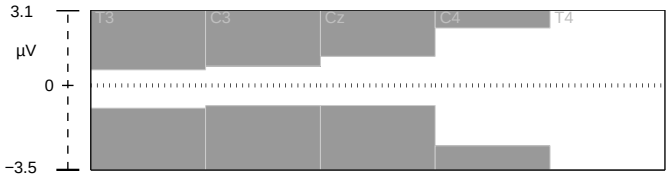

Fig. 8. Minmax plot containing five tiles, showing the extreme values for five electrodes. For the 100 data vectors shown in Fig. 7, the intervals containing no vector elements are excluded. The remaining area stays white. The amplitude scale is indicated with a dashed line on the left, while the zero-level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

vectors, two types of polyline density visualizations are employed. The first type uses histograms to show the distribution of the polylines along the parallel axes. These histograms can be superimposed on the vertical axes [19] or can be plotted separately beneath the axes [20]. The second density visualization type does not only replace the polylines by their densities along the axes, but also replaces the polyline density between the axes. Consequently, this type depends on the order of the axes. Examples are density plots, introduced by Wegman [21], and frequency plots [17]. A cluster visualization technique [16] is also of the second type.

Our method belongs to the first type, replacing the polylines along each axis by their density, and not between the axes. It does not explicitly show a histogram, but instead codes the histogram with grey scale values, resulting in a more intuitive density map (Fig. 9). Here, the grey value indicates the local density of the polylines along the axis, 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.

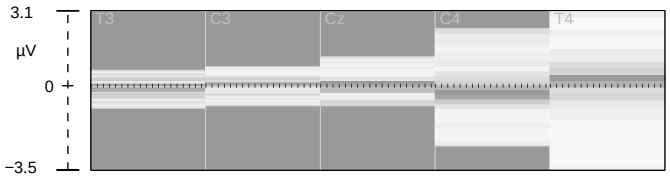

Fig. 9. Density map, combined with minmax plot, for the data in Fig. 7, reflecting the distribution of the polylines along the vertical axes (dark grey for high, light grey for low densities).

3) Combination of Parallel Coordinates, Minmax Plot and Density map: The grey scale density map leaves "visual space" for the additional use of color [22, p. 76]. Therefore, 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).

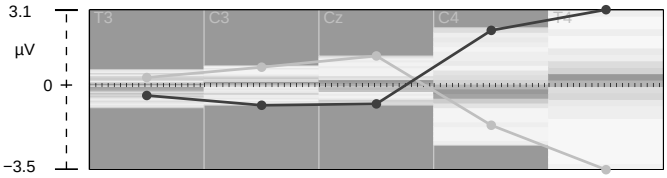

Fig. 10. Combination of parallel coordinates, the minmax plot, and the density map.

For a polyline corresponding to a particular moment in time, one can observe whether a measured value occurred frequently at a channel (the polyline crosses a dark grey region), or rarely (the polyline crosses a light region).

For the example in Fig. 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 electric potentials [23]. Large variations are associated with large changes in brain activity and are therefore assumed to be clinically relevant.

C. Tiled Parallel Coordinates

Instead of a one-dimensional arrangement of the tiles in columns, they can also be organized in a two-dimensional 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 Fig. 11, one for left-hand and one for right-hand stimulation. For both stimulations, two time instants are indicated by red and blue polylines. There is an overall voltage difference between left-hand and right-hand stimulation. Large amplitudes are mainly found on the side contralateral to stimulation. Further, per TPC map, many electrodes show contrasting amplitudes for the two selected time instants (red minima in combination with blue maxima, and vice versa). Comparing left median nerve stimulation to right median nerve stimulation, extreme values which are on the colored polylines for left-hand stimulation

have correspondingly colored extreme values on the contralateral side for the right-hand stimulation. Finally, the polylines colored correspondingly for both sides occur around the same time instants: for the red polyline, 0.021 s left versus 0.022 s right; for the blue polyline, 0.036 s left versus 0.041 s right.

A mirror symmetry in time and amplitude distribution is observed between the two TPC maps, for a healthy person. For patients with a certain type of neurodegenerative disease, this mirror symmetry may be distorted, which makes this visualization method potentially useful for clinical application.

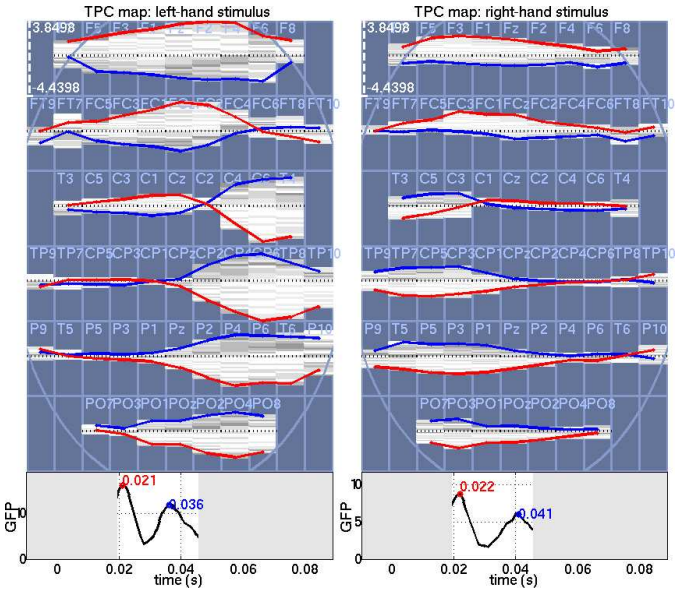

Fig. 11. Two TPC maps, both offering a top view of 58 electrodes (nose on top) and showing EEG data for left and right median nerve stimulation, respectively. Each tile corresponds to one electrode. The red and blue polylines correspond to two time steps. In the GFP plots below the TPC maps, the corresponding instants are indicated on the time axis in the same colors. For healthy persons, the left-hand and right-hand image are expected to be mirror-symmetric with respect to each other.

Although only 58 electrodes are shown, the TPC method can easily display 128 electrodes for both left-hand and right-hand stimuli (256 electrodes in total) on a single screen (cf. [1], Fig. 12). The previous density maps (Fig. 9) have been created for a number of 100 polylines, of which two are explicitly shown. However, the TPC maps are capable of representing many more polylines.

V. Qualitative Evaluation

To evaluate all EEG visualization methods mentioned in this paper, we present an overview of scores for four criteria. First, the number of time steps that can be visualized is indicated. Second, we assess the clarity of the time order. Third, the number of channels that can be properly analyzed is indicated. Finally, we express whether or not the spatial order of the channels is preserved. In table I, 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 to three dots for the highest score.

TABLE I
Scores for the basic EEG visualization methods.

	Methods	*Time* No.[1]	*Time* Order	*Channels* No.[2]	*Channels* Order
a	convent. EEG	●●	●●	●●	●
b	butterfly plot	●●	●●	●●●	
c	topogr. map	●●	●	●●●	●●
d	topogr. array	●●	●●	●●	●●
e	EP image	●●	●●	●●	●
f	par. coord.	●●		●●	●
g	tiled par. coord.	●●●	●	●●●	●●

[1]No. of time steps: ● 1; ●● $\sim$1,000; ●●● $\sim$100,000.
[2]No. of channels: ● 1; ●● 1-30; ●●● 30-128.

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

VI. User Evaluation

To carry out a user evaluation of the TPC method for multichannel EEG visualization, we compared it with an existing clinical multichannel visualization method to which we refer as *standard method*. The new method employed a single-page (size A4) visualization of TPC maps in combination with global field power (GFP) plots (Fig. 11). The standard visualization method consisted of a combination of conventional EEG representations (one page, cf. Fig. 1), butterfly plots (one page, cf. Fig. 2), and topographic maps (two pages, cf. Fig. 3).

TABLE II
MEAN EXPERIENCE (IN MONTHS) OF PARTICIPANTS IN THE USER EVALUATION WITH THE BASIC VISUALIZATION METHODS.

Method	*Students*	*Researchers*	*Clinicians*
conv. EEG[1]	19	177	120
butterfly[1]	4	42	20
topogr. map[1]	12	111	24
GFP plot[2]	2	12	12

[1]Part of the standard method.
[2]Part of the TPC method.

A. Goal

Typically, SEPs are assessed on the basis of latencies, amplitudes, and their symmetries. Our main aim was to find out how fast the TPC method is in comparison with the standard method for such an assessment, and how much information both visualization methods provide. In addition, we evaluated users opinions.

B. Participants

Twelve people participated in the evaluation, divided into three groups with different levels of experience with EEG assessment: five PhD or master students (‘students’), four researchers (‘researchers’), and three clinical EEG experts (‘clinicians’). All of the participants indicated their consent, allowing the observer to make voice recordings. They were instructed to work fast and accurately.

Table II shows the experience of the participants with each of the basic visualization methods which are part the evaluation. Researchers and clinicians are more experienced than students. Participants did not have much experience with the GFP plot, that is part of the TPC method. They had more experience with the basic methods which are part of the standard method. None of the participants had any practical experience with TPC maps.

C. Data

Sixteen different somatosensory evoked potential (SEP) data sets were visualized with both the standard and the TPC method: five data sets obtained from healthy controls, six from corticobasal degeneration (CBD [24]) patients, two from progressive supranuclear palsy (PSP [25]) patients, and three from patients with other diagnoses.

Four SEP components were selected as targets. The components are labeled N20, P25, N30, and P40. The label N20 is an abbreviation for a *n*egative component, with an expected latency of *20* ms. Other labels have similar meanings. Clinically, only the first of the components, the N20, is typically studied. However, later components may also have clinical value [6], [24], [25], [26], [27].

D. Task

During the evaluation, identical tasks were performed by the participants with both visualization methods. During a single task, three items had to be filled in for each of the four selected SEP components. They consisted of the latencies for the left-hand and right-hand responses and the mirror symmetry between this left-hand and right-hand response (figs. 3, 11). The latencies were given in milliseconds. A value for the mirror symmetry was scored on a five point rating scale, varying from ‘not symmetric at all’ (-2), via ‘neutral’ (0), to ‘very symmetric’ (+2). In addition, the overall mirror symmetry was assessed. Hereafter, we simply refer to mirror symmetry as symmetry.

In summary, a single task consisted of filling in eight latencies, four related symmetry values, and one overall symmetry value. Three TPC and three standard visualizations were shown after each other. Participants started alternately with the TPC method or the standard method.

Each participant saw a subset of the collection of sixteen data sets. A single participant completed as many tasks with the standard method as with the TPC method. Five participants completed twelve tasks, seven completed eighteen tasks. To ensure that participants did not recognize data sets, each participant saw the same data set at most once with each visualization method. The order of the data sets for each participant was determined semi-randomly, such that on average two out of three tasks were completed with the same data set for both the TPC and the standard method, and such that in every three data sets at least one data set was from a healthy control and one from a CBD patient. Each data set was seen by at least two participants. Because data sets were presented in this semi-random way, only 66 data sets were studied with both the TPC and the standard method and included in the following analyses.

E. Measurements

The following two items were measured for each participant and each task. *Time consumption* is defined as the time difference between receiving the printouts and filling in the last item on a form, minus the amount of time spent on questions during the task. *Information* is defined as the total number of latencies which was filled in (max. 8).

To test differences in time consumption, we performed a paired sample t-test. Differences in information, in symmetry assessment, and in subjective ratings were tested with a Wilcoxon paired sample test. Strengths of linear relationships were measured by Pearson's correlation coefficient [28].

Additionally, it would have been interesting to measure the accuracy of the information, i.e. the accuracy of the latencies. However, there is no gold standard to determine latencies.

F. Subjective Evaluation

A written post-test questionnaire [29, p. 199] provided quantitative ratings for several evaluation criteria. Participants were also given the opportunity to indicate any visualization element they liked or disliked, and to express ideas for future functionality.

G. Results

1) Objective Evaluation: One of the main evaluation aspects was time consumption. Overall, the TPC method was faster than the standard method (t-test, $p < 0.0005$). The time consumed with both the TPC method (mean M=163) and the standard method (M=277) was highly variable (with standard deviations SD=75 and SD=137, respectively). Also within each group (Fig. 12) the TPC method was faster (t-test: students $p < .0005$; researchers $p < .0005$; clinicians $p = .002$).

The temporal performance showed that per individual participant there was not much difference in time consumption between tasks, but that there were clear differences *between* individuals (see Fig. 13). Especially between the clinical experts there are large differences; from the fastest to the slowest clinical expert, the professional experience with conventional EEG is 20, 7, and 3 years, respectively. The time consumption using the TPC method correlated positively with the time consumption by the standard method (Pearson's $r = .674$, $p < .01$).

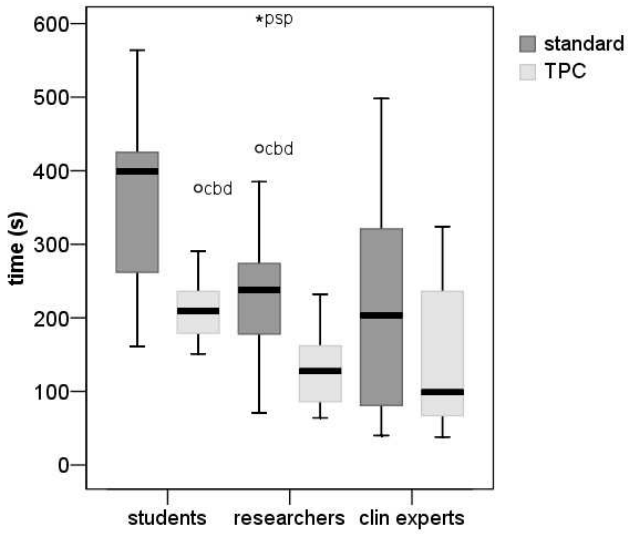

Fig. 12. Box-and-whisker plots for the timing consumption per group. Outliers (o) are more than 1.5 times the interquartile range away from the box, extreme values (*) more than 3 times. Labels of outliers indicate the data type.

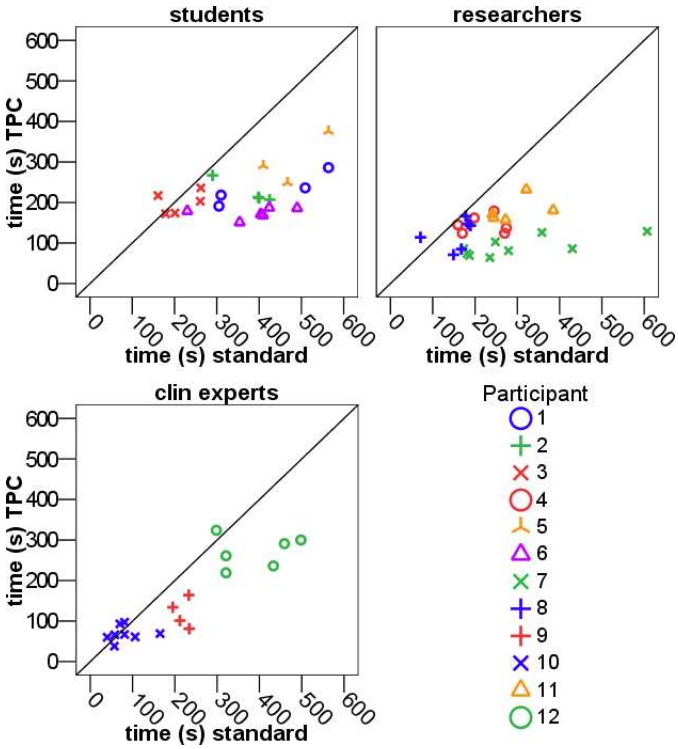

Fig. 13. Scatter plots with different symbols for different participants. Horizontally the time consumption using the standard method is indicated, vertically the time consumption using the TPC method. Symbols tend to cluster, implying individual scoring differences between participants. Most of the symbols are below the line ($y = x$), indicating that the TPC method was faster in most cases.

The other main evaluation aspect was information. There was no indication that the two visualization methods provided different amounts of in-

formation (Wilcoxon paired sample test, $p = .306$).

In Fig. 14, scatter plots illustrate the relation between time consumption and information. For the TPC method, there was no relation between the amount of information and the time consumption. On the other hand, only for students using the standard method, there was a positive relation between the amount of information and the completion time (Pearson's $r = .572$, $p < .01$).

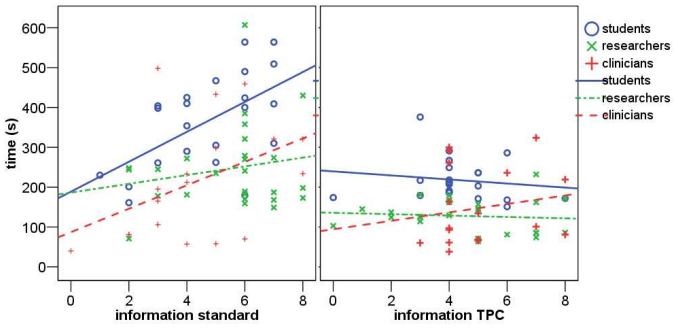

Fig. 14. Relation between time consumption and information, for the standard method (left) and the TPC method (right). Regression lines are displayed separately for students (solid), researchers (dot-dashed), and clinicians (dashed).

There was no difference between the time consumption regarding data sets of healthy controls or patients, neither for the standard method, nor for the TPC method.

Considering the assigned symmetry values, we expected data sets of healthy controls to be very symmetric, and those of CBD patients to be less symmetric. For these two data types, there was generally no difference between both visualization methods in the symmetry assessment. Only the N20 symmetry of healthy controls was assigned a higher value with the TPC method than with the standard method (Wilcoxon paired sample test, $p = .047$).

In clinical practice, differences between healthy people and patients are of prime importance. Fig. 15 shows the symmetry assessment for the N20 component by clinicians, for healthy controls and CBD patients separately. A clear difference was noticed. For the healthy controls, the N20 symmetry values assessed with the TPC method were higher than or equal to the values assessed with the standard method; for CBD patients it was the other way around. For the students and the researchers, there was no such difference in assessing healthy controls or CBD patients.

Table III shows the mean latencies (M) and the

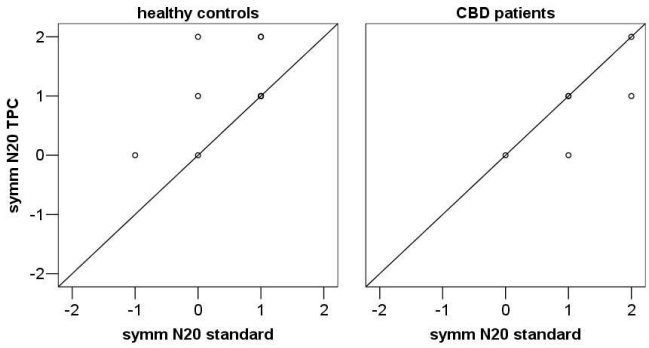

Fig. 15. Plots of N20 symmetry for the TPC method versus N20 symmetry for the standard method. For healthy controls (left) all circles are on or above the line $y = x$. For CBD patients (right) all circles are on or below this line. Note that one circle can represent several cases.

TABLE III
LATENCIES (MEAN AND STANDARD DEVIATION) FOR THE FOUR SELECTED SEP COMPONENTS, OBTAINED FROM DATA OF HEALTHY CONTROLS.

		standard. method		*TPC method*	
component		M	SD	M	SD
N20	L	21.5	0.91	21.4	0.90
	R	21.4	0.88	21.0	0.79
P25	L	25.0	0.82	25.2	0.40
	R	24.9	0.90	25.5	0.64
N30	L	32.8	5.00	33.2	3.45
	R	33.3	5.52	31.7	3.58
P40	L	46.0	2.35	42.8	2.71
	R	45.4	2.50	43.8	4.52

standard deviations (SD) for each of the SEP components, obtained from data sets of healthy controls. The values are grouped for the standard and the TPC method, and for left-hand (L) and right-hand (R) stimulation. No large differences were observed between the means of the standard method and the TPC method.

2) Subjective Evaluation: The participants were on average positive on all of the subjective criteria from the post-test form, for both methods. Differences were detected for only two criteria. Participants found the TPC method simpler (Wilcoxon paired sample test, $p = .033$) and experienced it to be faster (Wilcoxon paired sample test, $p = .023$), the latter in agreement with the objective time consumption studied before. Between the two methods, there was no difference for the properties: clarity; reliability; insightfulness; understandability; regular use (would you like to use this method more regularly); confusion-causing; agreeability; and color

TABLE IV
LIKED AND DISLIKED VISUALIZATION ELEMENTS.

	standard method[*]	*TPC method*[*]
liked	· topographic maps (6) · butterfly plot (4) · single conventional graphs (2) · time information (2) · availability of several visualizations (2)	· suitability symmetry assessment (4) · single glance overview (4) · GFP plot (2) · colored polylines (2)
disliked	· butterfly plot (6) · suitability symmetry assessment (2)	· only local maxima in GFP (6) · recognizability topogr. map (3)

[*] Between parentheses, the number of participants indicating the item is shown. Recall that there were in total 12 participants.

use. Furthermore, participants indicated that they would like both methods to be interactive and to give them an overview at a single glance.

At the end of the evaluation, participants were asked to indicate which elements they liked and which they disliked in each of the visualization methods. Table IV shows elements which were mentioned more than once. The topographic map was the favorite element of the standard method, the TPC method was favored for its suitability to assess symmetry and its characteristic to give an overview at a single glance. For the standard method the participants did not agree on the practicality of the butterfly plot; for the TPC method they did not agree on the practicality of the GFP plot.

Missed functionality was similar for both visualization methods. For the standard method, two participants would have liked to see interactive linked views for the standard method. For the TPC method, five participants preferred to see interactivity.

VII. DISCUSSION

In this paper, we surveyed existing visualization methods used for EEG data and proposed a new method, tiled parallel coordinate (TPC) maps, to visualize time-varying multichannel EEG data. The new method combines parallel coordinate plots 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 detects the moments of maximal variation of the electrode potentials.

The TPC method summarizes one-dimensional time information maintaining all spatial information, whereas other methods usually leave out part of the two-dimensional spatial information. As a result, the new method can handle more electrodes and more time steps simultaneously than existing EEG visualization methods. Although the TPC method has lost an explicit time order, some chronological ordering is still preserved by using linked views 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 electrodes than is possible with conventional parallel coordinates.

In a user evaluation, we compared the TPC method to a standard visualization method for multichannel EEG data. The participants were students, researchers, and clinicians. With both visualization methods, identical tasks were performed. A task contained typical SEP assessment elements, involving latencies, amplitudes, and their symmetries. Our main goal was to assess the time consumption and the amount of information given by both methods. In addition, we evaluated user opinions.

For the given task, the TPC method was on average about 40 % faster than the standard visualization method. This gain of speed was without loss of information, even though the TPC method only used a single page instead of the four pages required for the standard method.

There were clear speed differences between the individual participants, but from task to task there was not much difference within a single participant. For the TPC method, speed did generally not depend on the amount of information which was retrieved from the visualization. However, with the standard visualization method the speed sometimes decreased with an increasing amount of information.

Reported symmetry values were usually similar for both visualization methods. However, with the TPC method the assessed N20 symmetry values were different for healthy controls and CBD patients. This might have clinical value, to distinguish healthy people from patients.

The subjective opinions about the TPC method were positive and comparable to the opinions on the standard method, although the TPC method

was new to all participants except one. Considering simplicity, the TPC method was valued more highly. For the standard method the participants did not agree on the practicality of the butterfly plot; for the TPC method not on the GFP plot. For both visualization methods, interactivity was suggested to make these disagreements disappear.

The most preferred visualization element of the standard method was the topographic map. In the TPC maps on the other hand, the mapping of the activity was not that clearly recognized by a few participants. This recognition might however be a matter of experience, as the participants were familiar with the topographic maps from the standard method. The standard method was disadvantageous for studying amplitude variances and assessing symmetry. On the contrary, the best quality of the TPC method was to provide a quick overview from which symmetry can be assessed easily. The participants did not mention density maps as a (dis)liked element of the TPC method. Notwithstanding, density maps contribute to the identification of artifacts.

The power of the TPC method lies in the combination of the contextual features (minmax plot and density map) with selected polylines. For every electrode, it can be observed how large an amplitude is at one time step, compared to the amplitudes at other time steps at the same electrode, and compared to amplitudes at other electrodes. Alternatively, with topographic maps it is hard to study one position across several similar topographic maps, and to compare two positions in one map.

On the basis of this evaluation, we expect the TPC method to be very effective for researchers who study effects in healthy people. In addition, the method might be clinically useful. A future improvement would be to make the TPC method interactive, by linking the two views containing the TPC map and the GFP plot, and by implementing user-controlled brushing of time steps, tiles, and amplitudes. This allows users to study both expected and unexpected effects in as much detail as required.

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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Michael ten Caat obtained his M.Eng. in applied mathematics (2002) and his M.Sc. in numerical mathematics (2003) from the University of Groningen. He currently is a PhD candidate in the research group of Scientific Visualization and Computer Graphics within the department of Mathematics and Computing Science, University of Groningen. His research interests include scientific visualization and information visualization, especially neuroimaging and its scientific and clinical applications.

Natasha M. Maurits received her M.Eng. ('94) in applied mathematics, her M.Sc. ('94) in numerical mathematics and her Ph.D. ('98) in Chemistry, from the University of Groningen, the Netherlands. She is currently assistant professor in clinical neurophysiology with a special interest in biomedical signal analysis, in the department of Neurology of the University Medical Center Groningen. Her research interests include computational fluid dynamics models of the vascular circulation, analysis and clinical applications of multi-channel EEG and simultaneous EEG/EMG/fMRI recordings.

Jos B. T. M. Roerdink received his M.Sc. (1979) in theoretical physics from the University of Nijmegen, the Netherlands. Following his Ph.D. (1983) from the University of Utrecht and a two-year position (1983-1985) as a Postdoctoral Fellow at the University of California, San Diego, both in the area of stochastic processes, he joined the Centre for Mathematics and Computer Science in Amsterdam. There he worked from 1986-1992 on image processing and tomographic reconstruction. He is currently full professor of Scientific Visualization and Computer Graphics at the Institute for Mathematics and Computing Science of the University of Groningen, The Netherlands. His research interests include mathematical morphology, biomedical visualization, neuroimaging and bioinformatics.Biography text here.