Visual Comparison of Time-Varying Athletes' Performance

Fabian Beck, *Member, IEEE*, Michael Burch, and Daniel Weiskopf, *Member, IEEE*

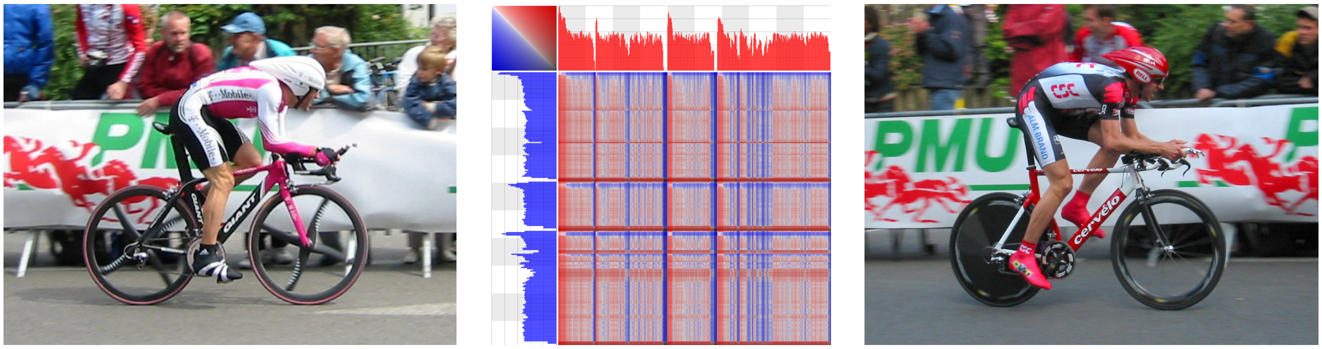

Fig. 1. Matrix-based visualization technique for comparing the time-varying performance of two athletes in time trials (e.g., road cycling).

Abstract—In the field of sports, large amounts of data are measured and stored with the help of modern electronic devices. In particular, for endurance sports events, time-varying data are recorded and can be used to analyze the athletes' performance. Finding patterns and issues can help to better understand results in sports competitions, which is of interest for the athletes themselves, sports managers, and trainers, but also for mass media and spectators. In this paper, we introduce a matrix-based concept to visually compare similar and dissimilar periods in performances of two athletes. We differentiate the performances and visually encode these differences as color-coded matrix cells. The strengths of our approach are illustrated in a case study investigating the performances of two riders in the prologue of Tour de France 2012.

Index Terms—Time series visualization, visual comparison, sports visualization, matrix visualization.

1 Introduction

Sports events have become a popular form of entertainment and, with the progress in technology, more and more data about the participating athletes can be measured, recorded, and stored. Typically, sports events span a predefined period of time or require to do a certain task as fast as possible—in either case, analysis involves time-varying performance data of the athletes. Visualization is particularly suitable to support analysts in an explorative inspection of such datasets because precise goals of the analysis might not be known in advance and questions can be multi-faceted. For the athletes themselves, their trainers, and managers, visualizations could help to react on possible problems either during the event or in retrospective analysis. Moreover, for the mass media, visual representations of data are a welcomed means to illustrate and communicate stories of the sports event to spectators.

While it is already interesting to analyze the performance of a single athlete, this perspective sometimes lacks a reference to judge the performance and to reveal potential for improvement. Providing a static, absolute standard, however, is difficult because the athlete's performance is time-dependent. A better criterion could be to take a different athlete's performance as a reference. A comparison like that might tell what one athlete does better than the other or could reveal different tactics they use. While there often exist straightforward ways to just overlay or juxtapose standard diagrams reflecting the performance of different athletes, developing visualizations explicitly designed for comparison could even provide more powerful tools.

• *All authors are with VISUS, University of Stuttgart, Germany. E-mail: {fabian.beck,michael.burch,weiskopf}@visus.uni-stuttgart.de.*

Manuscript received 31 March 2013; accepted 1 August 2013; posted online 13 October 2013; mailed on 4 October 2013.
For information on obtaining reprints of this article, please send e-mail to: tvcg@computer.org.

In this paper we introduce a matrix-based visualization approach to specifically compare time-varying athletes' performance. To the best of our knowledge, the approach is novel and extends state of the art (Section 2). As an underlying concept for the visualization, a performance difference is used as a difference measure (Section 3). The resulting differences are depicted in a color-coded matrix representation where the axes represent the time lines for two athletes to be compared, or for two repetitions of the same challenge for a single athlete (Section 4). Performance, in the context of this work, can be regarded as a quantitative measure of the behavior or state of the athlete, such as the traveled distance, velocity, acceleration, and the like; the approach is applicable to many sport disciplines (Section 5). Our technique is illustrated by a case study investigating time series data for cyclists acquired during the prologue of Tour de France 2012 (Section 6).

2 Related Work

There are various visualization techniques that represent time-varying data [2]. For instance, analyzing temporal changes of quantities is of special interest for medicine when predicting heart diseases or heart attacks, for geology when predicting earthquakes, or for judging the extent of flood waves. Dynamic quantities are a simple form of time-varying data because only one variable is changing over time. Visualizing such data is intuitive by just plotting the points at each time step in a Cartesian coordinate system and possibly connecting two subsequent points by a line. In literature such diagrams are referred to as line plots [12]. Comparing several dynamic quantities, line plots are oftentimes aligned and plotted into the same coordinate system; different colors or stroke styles can be used to distinguish a small number of those lines. Alternatively, avoiding the overplotting of lines, a so-called ThemeRiver visualization [9] represents time series as river-like shapes stacked on top of each other. Although this concept produces aesthetically pleasing diagrams and has been adopted by other researchers [11], it becomes difficult to compare quantities over time. As evaluated by Cleveland and McGill [5], a common baseline aligning the quantities is missing. Krstajic et al. [10] therefore propose CloudLines where each river has its own baseline to circumvent this problem. The TimeEdgeTrees [4] use a similar concept encoding multiple time series embedded into a hierarchy. Those techniques working with small multiples of diagram, however, require jumping back and forth between the diagrams to conduct a comparison; in particular, comparing the exact same positions in time becomes difficult.

There do not exist many approaches that explicitly encode the comparison of time series, i.e., compute a comparison and visualize the result of this. According to the taxonomy of Gleicher et al. [7], an explicit encoding is one of three main approaches of visual comparison; the other techniques described above can be mostly classified either as superposition (overlay) or juxtaposition (small multiples). A simple explicit encoding for the visual comparison of time series would be to compute the difference of the time series and visualize the resulting difference time series, for instance, as a line plot [7]. Beyond that, we are not aware of other explicit encoding techniques for time series comparison, in particular not of any matrix-based approach like the one we present in this paper.

Matrix-based techniques have been used, however, for the comparison of other kinds of data. For instance, bioinformatics researchers work with dot plot matrices [6] for comparing DNA or RNA sequences. Matrix representations are also employed for comparing vertex sets in graphs plotting the vertices to the axis of the matrix and marking adjacencies in the cells of the matrix [1, 3]. Also the comparison of hierarchies can be implemented by marking cells areas of a matrix while having the two hierarchies attached to axes of the matrix [3, 8].

3 Data Model

In the context of this work, we model a time series S as a finite sequence of n data points

$$S := \{v_1, \ldots, v_n\}$$

where $v_i \in \mathbb{R}$. Depending on the sports events, the time series can represent different kinds of performance data of a single athlete. Multiple aligned time series of the same length representing different measures might be available. Usually, an additional time series

$$S^t = \{v_1^t, \ldots, v_n^t\}$$

should be provided that includes all the time stamps of the data points—discerning between actual time series used for the comparison S and respective time stamps S^t allows for handling gapped time series as well as varying sampling rates. The approach is able to compare two time series

$$S_1 := \{v_1, \ldots, v_n\}$$
$$S_2 := \{w_1, \ldots, w_m\}$$

of length n and m accompanied by two time stamp series S_1^t and S_2^t. The two time series could either represent the performances of two different athletes or repetitions of performances of the same athlete—in either case, the underlying challenge should have been equivalent for the sake of fair comparison. For contrasting any two data points v_i and w_j of two time series S_1 and S_2, a difference measure

$$\delta : S_1 \times S_2 \longrightarrow \mathbb{R}$$

is required. This function allows comparisons between arbitrary data points; the result will be explicitly encoded in the visualization. The most straightforward definition of the difference measure is

$$\delta := v_i - w_j,$$

which we use in the following. Additionally, we introduce a function

$$\sigma : S_1 \times S_2 \longrightarrow \mathbb{R}$$

that should not reflect the difference of the compared data points but their aggregation; its easiest definition is

$$\sigma := v_i + w_j.$$

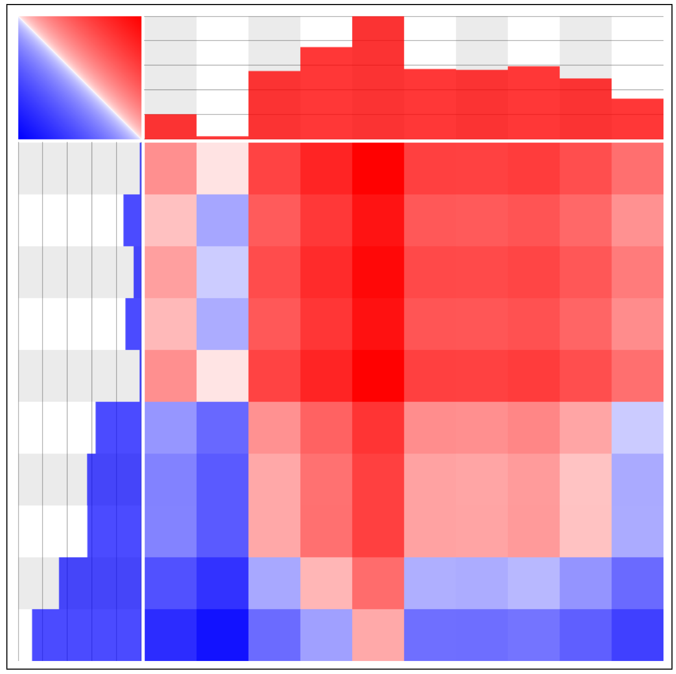

Fig. 2. Small sample data set visualized with the *simple* time series comparison technique.

This aggregation measure σ will be used in the visualization as an additional augmentation of the difference measure δ for an advanced comparison approach.

4 Visualization Technique

Our proposed visualization technique is based on a matrix view with the time series attached to the axes. Both time series start in the upper left corner; while time series S_1 is aligned horizontally and ends on the right, time series S_2 goes vertically to the bottom of the diagram. The matrix in the middle provides a visual comparison of the two time series. The visualization technique employing a simple visual comparison approach is illustrated in Figure 2, which compares two time series each having ten data points; in addition, Figure 3 shows the same data based on an extended comparison approach.

4.1 Time Series Visualization

The two time series visualizations attached to the matrix are standard bar chart plots, however, one of them not aligned from left to right but from top to bottom. Two colors, red and blue, are used to consistently discern the two diagrams from each other. The length of the bar, encoding a value v_i or w_j of the series, follows the same scale in both diagrams (i.e., the same length always encodes the same absolute value). While all examples in this paper use linear scales, logarithmic or other scaling could be applied as well if necessary.

The decision to use filled bar charts instead of line charts for encoding the time series was motivated by multiple reasons: first, bars better reflect the discrete nature of the sampled time series than continuous lines; second, the bars intuitively show the orientation of the horizontal axis in the rotated time series plot (i.e., values increase from right to left, not vice versa); and third, the quantity of colored screen space increasing with the values of the time series provides a metaphor that can be further exploited for encoding differences as explained in the following.

4.2 Simple Time Series Comparison

The matrix in the center of the diagram encodes the comparison of the two time series as shown in Figure 2 for the simple comparison approach. Each cell in the matrix represents the comparison of two data points: the data point in the respective column of time series S_1

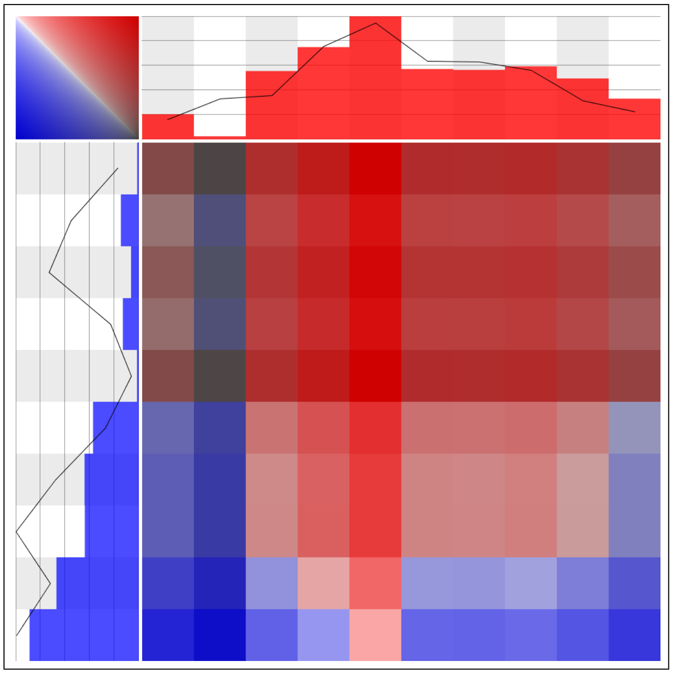

Fig. 3. The same data set as shown in Figure 2 visualized with the *advanced* time series comparison technique and additional line plots.

(red diagram) and the data point of the respective row of time series S_2 (blue diagram). In the simple comparison approach, only the difference measure δ of the two data points is reflected in the color: red represents positive values of δ (higher value in the red diagram), blue negative values (a higher value in the blue diagram), and white balanced values around $\delta = 0$. Transitions between colors are continuous, but non-linear to have a higher color-resolution for more frequently occurring small difference values. The color scale is provided in the left upper corner of the diagram as a static color legend; the scale of the bar chart diagrams applies to the color legend as well, so that two values in both diagrams can be manually resolved to a color. Since different combinations of values map to the same value of δ, those combinations will have the same color in the visualization.

Since we potentially handle long time series, we need to discuss visual scalability. Following the proposed approach, it can be possible that multiple cells of the matrix are mapped to the same pixel on screen. Generally, there exist two ways of dealing with this issue:

- **Data Overplotting:** Overplotting of data points means processing the data points one-by-one and always draw the actually processed data point in its corresponding color coding to the location on screen. If the data points are processed in their temporal order this means only the point representing the latest time step that falls in the same matrix entry as the earlier ones is displayed to the viewer. This naive rendering approach may produce unintuitive color coded matrices, but more advanced rendering techniques can be applied to improve the result.

- **Data Aggregation:** Aggregation of data points generally means looking up all data points first that fall into the same matrix cell. All candidates are taken into account for computing a specific color coding of the corresponding matrix cell. Here, several schemata might be used: The maximal value, the average value, or the sum of all values can be computed. The applied color coding is generated by taking the maximal possible value into account and by computing the percentage of the actual value to this maximum.

The current implementation of our approach only works with overplotting, which renders cells partly transparent if they should fill only a fraction of a pixel. In general, the approach, however, is open to every kind of more advanced rendering technique with respect to overplotting as well as to data aggregation.

The uncommon and novel encoding of the difference values in the matrix allows, in contrast to standard overlaid line charts, compare data points or subsequences of the time series independently of shifts in time: without changing the image, just by looking at different areas of the matrix, the first data points of S_1 can be compared to the first data points of S_2 as well as to last ones of S_2. The visualization also supports the balancing of different scaling in the two compared diagrams, which just requires analyzing a non-quadratic, rectangular region of the matrix. As a consequence, it is not a problem for the visualization approach if the time series have different length ($n \neq m$), the sampling rate varies, or the time series were not aligned properly. The matrix comparison encodes all possible $n \times m$ comparisons while overlaid line charts only depict $\min(n,m)$ direct comparisons (additional indirect comparisons are possible in a certain spatial environment of the data points).

4.3 Advanced Time Series Comparison

Although the absolute values of the time series can be retrieved from the attached bar charts, it would be helpful being able to directly estimate the absolute values from the matrix: for instance, it could make a big difference for the interpretation if a balanced difference is caused by two small values or two large ones. As an advanced comparison approach illustrated in Figure 3, we hence propose to vary the brightness of color coding to additionally encode the absolute values based on the aggregation measure σ. Mapping σ to a brightness scale and applying that to the previously described color scale makes the resulting color unique for every combination of values. For instance, a very bright red color then indicates a very high value of S_1 and a medium one for S_2 or a dark gray color represents two balanced but low values in the two time series. A non-linear mapping of values to the brightness scale is applied because it is difficult to discern colors of very dark colors. Again, the color scale, now varying in two dimensions, is provided in the upper left corner of the visualization and can be read as before.

The design of the visualization technique allows for easy encoding of additional information such as further time series. To implement that, we propose to plot the time series as line plots and overlay these on the bar charts as also demonstrated in Figure 3. The different chart styles (bars and lines) clearly indicate the different role of the time series: while the *heavy* bar charts form the basis for the comparison, the *light* line charts just provide additional information. Though multiple line charts can be overlaid at the same time and discerned by color, we just use examples with one additional time series because the diagram can quickly become overloaded with information when adding more data.

5 Applicability in Sports Analytics

Our visualization technique for comparing time series is suitable for performance data of athletes, particularly when athletes try mastering the exact same challenge in the shortest possible time. It works for the comparison of two athletes as well as for the repetition of the same challenge of a single athlete. The approach is applicable to all kinds of endurance sports, such as running, cycling, swimming, cross-country skiing, rowing, etc., but also to other sports such as motor sports or alpine skiing. Depending on the kind of sports, however, different measures might be of interest that should be compared with the visualization. While speed might be a universally valid attribute, others are more sports-specific, such as applied force, heart rate, fuel consumption, acceleration, altitude, etc. A limitation of the approach is that only two time series can be compared at the same time. It is further not applicable to most team sports, which usually have not uniform time challenges. In general, the visualization is targeted at athletes, coaches, sport consultants, sport researchers, journalists, and engaged fans. Its flexibility in handling non-aligned or non-uniformly scaled time series makes it easy to use and increases its general applicability.

6 CASE STUDY: CYCLING TIME TRIALS

For this case study, we investigate the example of cycling time trials. In particular, we analyze data of two riders from the prologue of the Tour de France 2012[1]. The prologue is a short time trial race where all riders are sent on the track separately, one after the other, and slip-streaming (which can have a big impact in road cycling) is forbidden. The 2012 prologue of the Tour de France was carried out in Liège, Belgium on a 6.4 km track without any relevant ascents. Fabian Cancellara, a Swiss time-trial specialist from Team Radioshack-Nissan, won the stage in 7' 13".

For this stage, Peaksware, a company that sells analytics software for cycling professionals called TrainingPeaks, published recorded performance data of a small number of riders[2]. In the following, we compare the performance of Kanstantsin Sivtsov, a Belarusian rider from Team Sky Procycling, against equivalent data of Janez Brajkovic, a Slowenian member of the Astana Pro Team (the two riders shown in Figure 1 are other cyclists; pictures were taken at the prologue of Tour de France 2004 that also happened to be situated in Liège, Belgium). While Sivtsov finished 63rd out of 198 cyclists, 0' 25" behind the winner Cancellara, Brajkovic was ranked 32nd with only 0' 22" time difference to the winner. The data sets are available in PWX format, an XML-based format specified by Peaksware that potentially contains time series data on heart rate of the cyclist, current speed, pedal power, pedal cadence, traveled distance, current altitude, and outside temperature. The provided data for the two riders only covers parts of this information and are recorded with a sampling rate of one second for Sivtsov and only every two seconds for Brajkovic. Including not only the race, but also race preparation (with gaps), the data sets span 148' 25" (5,522 data points) for Sivtsov and 284' 01" (3,304 data points) for Brajkovic, i.e., the actual race is only a small subset of the data.

The case study is based on two visualizations comparing the performance measured as the power used for pedaling of the two cyclists: while Figure 4 provides an overview on the complete data sets including the race preparation and race (no preprocessing or alignment was applied), Figure 5 shows details on the race periods in larger resolution. In order to create space-efficient visualizations, time periods without recorded data are skipped and the progress of time is presented as an additional line plot to mark the gaps in Figure 4; since there were no gaps in recording during the race periods, this additional encoding is not necessary for Figure 5.

6.1 Race Preparation

Analyzing the complete data sets in Figure 4, we can confirm from the visualization that the race itself, which can be easily detected as a period of high and constant performance values, covers only a short time span at the end of the time series. This can either be detected by looking at each time series individually or by searching for the brightest area within the matrix. This area actually conforms to what is depicted at a higher resolution in Figure 5 and will be discussed below. Figure 4 is more suitable for analyzing and contrasting the race preparation strategies (and follow-up activities) of the two athletes.

For every of the two riders, the preparation phase falls into two parts, which is indicated by larger jumps in the additional time series as well as by different patterns in the bar charts and matrix. We assume that the first part was recorded while the riders cycled on the road because the performance values are varying more chaotically: while being on the road, the cyclists have to slow down for bends or obstacles like other cyclists, cars, or pedestrians, that can be still on the track during race preparation. The comparable, repetitive patterns of similar length within the time series of the two riders (bar charts) as well as in between of the riders (matrix) further indicate that both drove four laps on a similar track. Comparing those laps to the race period in the matrix even suggests that this track was the later race track: the matrix shows quite homogeneous red or blue areas at the intersections of the early preparation phase and the race, i.e., the athletes' performances follow the same pattern but just on a consistently lower level. The dominating red color at the upper left corner of the matrix shows that first Sivtsov trained harder for the first three training laps; the last lap, however, Brajkovic powered more as indicated by blue color in the matrix.

The second phase of the preparation is dominated by more regular patterns, which can hardly be achieved when cycling on the road, but require a more controlled environment as probably provided through bicycle rollers (i.e., a training device similar to a stationary bicycle but that can be used with the road bicycle). Brajkovic trained multiple intervals of constantly increasing intensity; a sudden drop in intensity marks the beginning of a new interval. Indicated through diagonal patterns in the matrix, a similar pattern can be observed just once for Sivtsov, who spans this single interval, however, over a much longer period. Sivtsov used the second half of this controlled training phase for constant intensity training with three extreme but short peaks at the end. These peaks are reflected in isolated vertical red lines in the matrix—equivalent blue horizontal lines indicating similar peaks for Brajkovic are not detectable. In total, Brajkovic spent more time on this second preparation phase than Sivtsov, but including a shorter period of relative inactivity directly before the race. After the race Brajkovic, seemed to continue with some training on bicycle rollers (regular pattern), while the recording for Sivtsov ends shortly after the race.

6.2 Race

The race itself can be better analyzed in Figure 5, which compares the two respective race periods in an enlarged version. The matrix showing the comparison is dominated by two vertical and two horizontal color-intense lines and is divided by these into regular squares. The lines are caused by two sudden drops in power at the same time of the race for both riders. These parallel short phases of rolling hint at sharp bends in the track—looking at the map of the course[3], we find indeed two 180° bends at about the middle of the distance. Further, weaker horizontal and vertical lines, symmetrically for both cyclists, indicate weaker bends or other obstacle on the track. The first drop of power as well as the following climb, however, is much stronger for Sivtsov than for Brajkovic as the more intense vertical than horizontal lines show; Sivtsov hence may have had more problems mastering this first obstacle.

In general, the whole matrix area of Figure 5 is colored in a bright mixture of blue, red, and white, only with exceptions of the already discussed color-intense vertical and horizontal lines. Neither blue nor red is dominating: none of the riders seems to have performed consistently better. This can be confirmed by looking at the total time difference between the two athletes, which was only 0' 03" at the finish line. Since there can be many reasons that explain the small difference, it might be too ambitious trying to name the reasons just through the use of visualizations. Nevertheless, our visualization reveals subtle differences between the riders that could have influenced the total time: high-frequent vertical stripes in the matrix are somewhat more distinguished than equivalent horizontal ones, which shows that the performance of Sivtsov is varying more than the performance of Brajkovic. In particular, after the second 180° bend, Sivtsov's performance has a much more irregular pattern than Brajkovic's. These observations together with observations from the race preparation might point to potential issues and could help the athlete and trainer to improve the athlete's performance beyond just trying to blindly increase overall fitness.

7 CONCLUSION AND FUTURE WORK

In this paper we illustrated how two time series can be visually compared by using a matrix representation. The novel concept of showing

[1] `http://www.letour.fr/le-tour/2012/us/prologue.html`; last retrieved on 08/29/13

[2] `http://home.trainingpeaks.com/races/tour-de-france/2012/prologue.aspx`; last retrieved on 08/29/2013

[3] `http://www.letour.fr/2012/TDF/COURSE/us/0/etape_par_etape.html`; last retrieved on 09/05/13

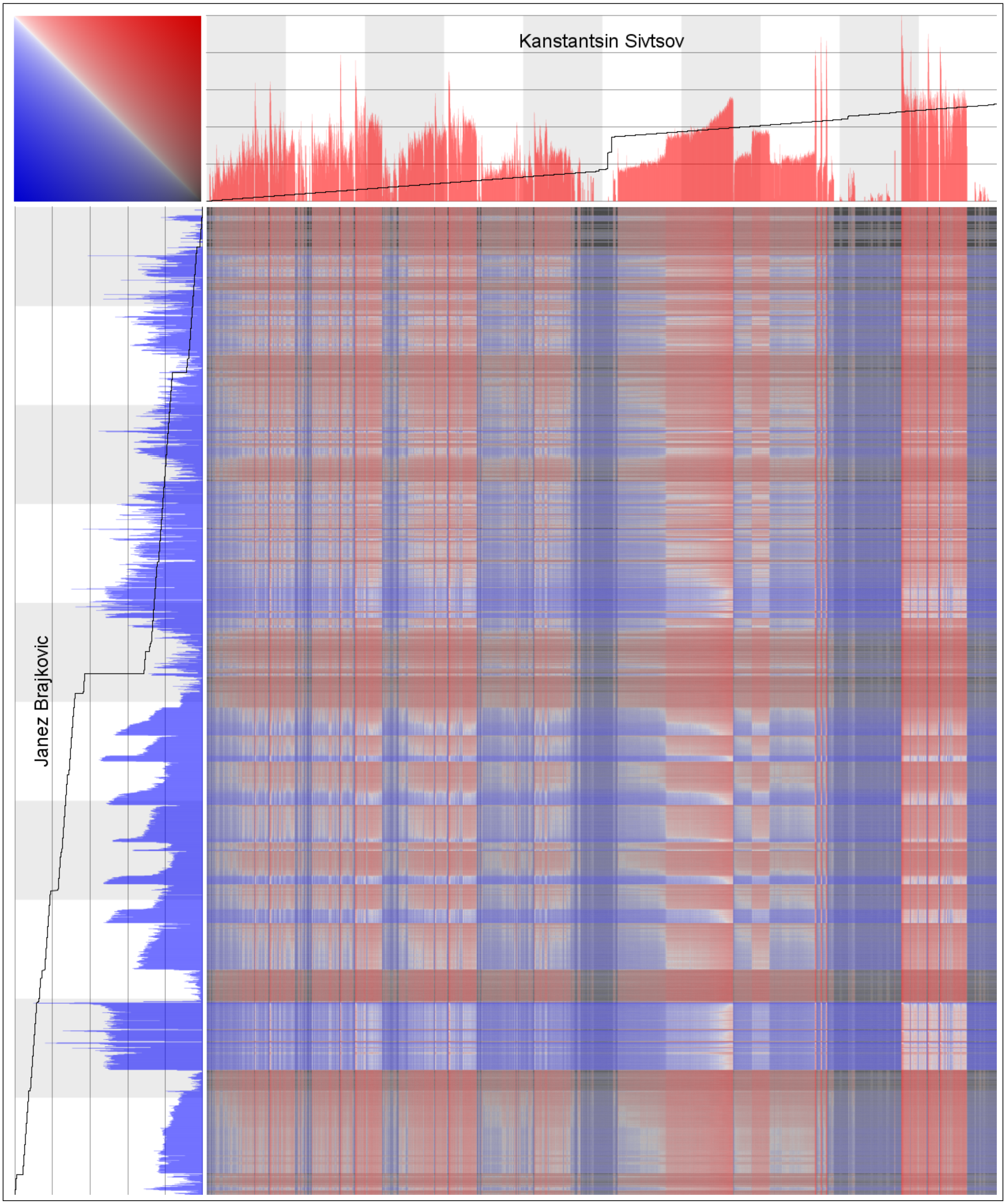

Fig. 4. Comparing the performance (power) of Kanstantsin Sivtsov (red) against Janez Brajkovic (blue) in the prologue of Tour de France 2012 including their preparation period for the race; the additional line chart reflects the progress of time and indicates gaps in measurement.

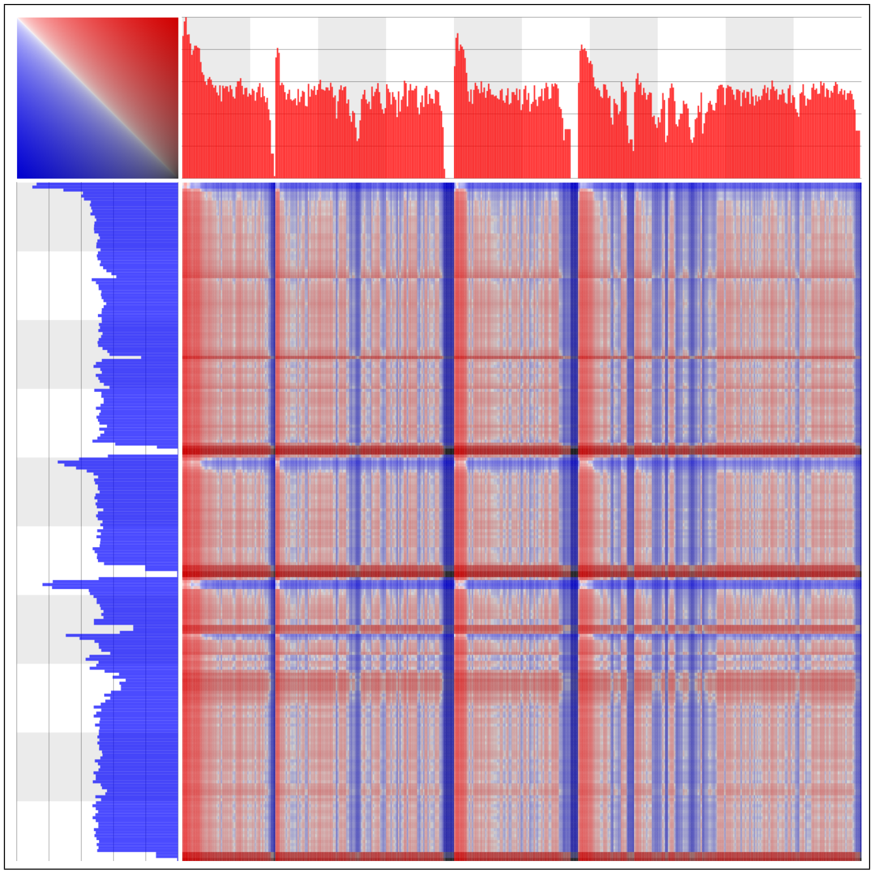

Fig. 5. Focusing the data of Figure 4 on the actual race periods.

comparisons of data points as color-coded matrix cells is simple, yet powerful: in contrast to overlaid line plots, our approach allows for the comparison of any shifted and scaled periods within a single static diagram because all pairwise combinations of data points are represented. This advantage may come at the costs of a less intuitive representation and a more difficult comparison of concurrent data points. A further limitation is that only two time series can be compared at the same time; it might be possible, however, to extend the approach to $n \times m$ comparisons similarly realized in a scatterplot matrix for displaying multivariate data. The case study provides first evidence on the applicability and utility of the visualization approach in the area of sports visualization. Though being only tested on data from a bicycle time trial, it is likely that the visualization will also be suitable for analyzing other kinds of endurance sports events. In particular, the visualization revealed different preparation strategies for the race of the two compared athletes as well as subtle differences in race performance. As part of future work, we plan to explore the usefulness of the approach in other areas of application, to study how interaction techniques could support the analysis, and to evaluate the tool against traditional comparison techniques for time series data.

Acknowledgments

The authors wish to thank Sabrina Ehses for granting permission to use her photos for Figure 1.

References

[1] A. Abuthawabeh, F. Beck, D. Zeckzer, and S. Diehl. Finding structures in multi-type code couplings with node-link and matrix visualizations. In *VISSOFT '13: Proceedings of the 1st IEEE Working Conference on Software Visualization*. IEEE Computer Society, 2013.

[2] W. Aigner, S. Miksch, H. Schumann, and C. Tominski. *Visualization of Time-Oriented Data*. Human-Computer Interaction Series. Springer, 2011.

[3] F. Beck and S. Diehl. Visual comparison of software architectures. *Information Visualization*, 12(2):178–199, 2013.

[4] M. Burch and D. Weiskopf. Visualizing dynamic quantitative data in hierarchies - TimeEdgeTrees: Attaching dynamic weights to tree edges. In *IMAGAPP/IVAPP*, pages 177–186, 2011.

[5] W. S. Cleveland and R. McGill. An experiment in graphical perception. *International Journal of Man-Machine Studies*, 25(5):491–501, 1986.

[6] A. J. Gibbs and G. A. McIntyre. The diagram, a method for comparing sequences. Its use with amino acid and nucleotide sequences. *European Journal of Biochem*, 16:1–11, 1970.

[7] M. Gleicher, D. Albers, R. Walker, I. Jusufi, C. D. Hansen, and J. C. Roberts. Visual comparison for information visualization. *Information Visualization*, 10(4):289–309, 2011.

[8] M. Graham and J. Kennedy. A survey of multiple tree visualisation. *Information Visualization*, 9(4):235–252, 2009.

[9] S. Havre, E. G. Hetzler, P. Whitney, and L. T. Nowell. ThemeRiver: Visualizing thematic changes in large document collections. *IEEE Transactions on Visualization and Computer Graphics*, 8(1):9–20, 2002.

[10] M. Krstajic, E. Bertini, and D. A. Keim. CloudLines: Compact display of event episodes in multiple time-series. *IEEE Transactions on Visualization and Computer Graphics*, 17(12):2432–2439, 2011.

[11] C. Shi, W. Cui, S. Liu, P. Xu, W. Chen, and H. Qu. RankExplorer: Visualization of ranking changes in large time series data. *IEEE Transactions on Visualization and Computer Graphics*, 18(12):2669–2678, 2012.

[12] E. R. Tufte. *The Visual Display of Quantitative Information*. Graphics Press, Cheshire, CT, USA, 1992.