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**DOI**

[10.1111/cgf.14722](https://doi.org/10.1111/cgf.14722)

**Publication date**

2022

**Document Version**

Final published version

**Published in**

Computer Graphics Forum

**Citation (APA)**

Pieras, M., Marroquim, R., Broekens, D., Eisemann, E., & Vilanova, A. (2022). ComVis-Sail: Comparative Sailing Performance Visualization for Coaching. *Computer Graphics Forum*, 42 (2023)(1), 86-100. <https://doi.org/10.1111/cgf.14722>

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# ComVis-Sail: Comparative Sailing Performance Visualization for Coaching

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## Abstract

*During training sessions, sailors rely on feedback provided by the coaches to reinforce their skills and improve their performance. Nowadays, the incorporation of sensors on the boats enables coaches to potentially provide more informed feedback to the sailors. A common exercise during practice sessions, consists of two boats of the same class, sailing side by side in a straight line with different boat handling techniques. Coaches try to understand which techniques are that make one boat go faster than the other. The analysis of the obtained data from the boats is challenging given its multi-dimensional, time-varying and spatial nature. At present, coaches only rely on aggregated statistics reducing the complexity of the data, hereby losing local and temporal information. We describe a new domain characterization and present a visualization design that allows coaches to analyse the data, structuring their analysis and explore the data from different perspectives. A central element of the tool is the glyph design to intuitively represent and aggregate multiple aspects of the sensor data. We have conducted multiple user studies with naive users, sailors and coaches to evaluate the design and potential of the overall tool.*

**Keywords:** visual analytics, visualization, information visualization, • Human-centred computing → Information visualization

**CCS Concepts:** • Human-centred computing → Information visualization

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## 1. Introduction

Sports visualization has become an active research [GKW13] field that investigates new approaches for exploration, sense making and communication [PVS\*18] for sports data.

The incorporation of measurement devices (i.e. GPS units, heart-rate monitors) enables collecting new data to help understanding an athlete's performance. The acquired data are commonly multivariate, time-varying, spatio-temporal, heterogeneous, complex and, in general, difficult to analyse. Summary statistics or simple direct visualizations of the acquired signals are often used, but are not enough to explore the data effectively. Visual analysis tools are promising strategies to aid exploration and to gain new insights from the data. For example, the reason that makes an athlete perform better depends on a wide range of factors and it is commonly not well-understood. Data analysis provides new ways to answer typical questions, like: Why does athlete *A* perform better than *B* and which conditions increase athlete *A*'s performance?. Sports visu-

alization solutions are application-specific. Each sport has specific characteristics that require tailored solutions to achieve effective visual analysis. Notwithstanding, there are tasks and data abstractions that can be generalized to multiple sports.

In this paper, we focus on sailing where athletes have to make decisions based on diverse and complex inputs; the weather, the boat settings, the boat handling and their own physical condition. Recently, the miniaturization of sensors allowed their deployment in this harsh environment, without interfering with the boat handling.

Like in other sports, during training sessions, a technique is repeated until mastered. However, weather conditions, like wind and currents, are difficult to control and, therefore, specific training strategies are used. A common exercise, called *Line-up*, consists of two boats sailing side-by-side in a straight line with different initial settings and handling. Coaches try to understand their effect on the boat's speed.

Currently, this coaching process relies on rather rough visual observations during training and coarse analysis. The coach cannot pay attention to the multiple variables involved in boat handling that are tested, while simultaneously having a global and context-aware view. For instance, a coach might compare the rudder movement between boats but will miss the complete view on other variables.

Multiple sensors are deployed in boats during the *Line-up* training. At present, aggregated statistics are used to reduce the complexity of the data but hereby local and temporal information is lost. Similar problems have been tackled, for instance, in the work of Polk *et al.* [PJHY20], spatial-temporal data from tennis matches are analysed to improve coaching. However, these solutions are specific for sports that are rather different in nature from sailing. Therefore, they are not directly applicable and, to the best of our knowledge, no visual analysis solution has been proposed for sailing in this context.

The main contribution of our work is the design of a visualization tool, i.e. ComVis-Sail, that allows coaches to visually explore and compare sensor data from boats. ComVis-Sail is designed to help answering the main question: *what behaviour makes one boat go faster than the other?*.

A central aspect of the visual design is the mapping of the multivariate information to a comprehensive glyph to increase the expressiveness of the encoding. The proposed glyph allows seamless transition from instant multivariate information, to summarizing multiple time points. The design choice and effectiveness are evaluated through a user study with multiple users with different backgrounds.

Our overall approach combines spatio-temporal and multivariate aspects of the data with special emphasis on comparison. The design is achieved alongside sailing experts through an iterative process. ComVis-Sail has been used in multiple training sessions and a continuous user evaluation shows the effectiveness of the design and the potential of ComVis-Sail.

Our work and lessons learned can be generalized to other racing sports, where high-frequency data can be captured and similar questions and tasks are relevant, like car racing [LB15], marathon running [OCT\*13] or time trial on road cycling [BBW16].

The rest of the paper is organized as follows: Section 2 presents the related work. Section 3 provides background knowledge on sailing. Sections 4 and 5 present the domain and data analysis of the problem we tackled, and Section 7 explains the task that our visualization targets. Section 8 describes the visual encodings of ComVis-Sail. Section 9 presents the user evaluation we carried out with sailor experts. Finally, Section 10 presents our conclusions and future work.

## 2. Related Work

Sports visualisation has become a popular research topic during the last years, with an increasing number of publications at leading conference such as IEEE VIS [GKW13], EuroVIS [PVS\*18] and ACM CHI [NTMM14]. It also received attention in the mass-media ecosystem, like newspapers [QR], television [TV218] and specialized blogs [Pai20].

Our work aims at an *analytic* solution rather than narrative [PVS\*18]. Analytical sports data visualization provides a way to understand an individual or a team performance. Here, the analyst might not have specific hypotheses regarding reasons for a certain performance and data exploration can be key to discover unexpected insights.

Sports, in general are full of comparisons. In some sports, a simple goal or points measure indicates which team is ahead. Yet, in addition, you want to establish where the differences in performance are coming from. At this level, it gets more specific depending on the sport. For instance, in Soccer, it is common to compare ball possession while in Tennis, the number of *unforced errors* gives important insights on the athletes' performances [PJHY20].

The main literature on sports data visualization focus on mainstream sports like soccer [AAB\*17], basketball [Gol12] or baseball [DKVS14], where especially the relation between different players contributes to the best performance of the team. On the other hand, little attention has been given to non-mainstream sports [DY20]. To the best of our knowledge, there is limited work in the area of comparison of individual competitors sports [BBW16, ZCY\*19, LLW\*20].

Moreover, we target comparing multi-dimensional time-varying data, differing from the main trend in sports visualization based on event data visualization. Nevertheless, we can fit our data in the broader classification of *tracking data*, which corresponds to continuous spatio-temporal motion captured by sensors or video. There are similar works analysing trajectories of soccer players [WXW\*19, AAA\*21], they focus on how to arrange the spatial characteristics of multiple players to analyse their collective strategy rather than their sensory data.

Hence, we borrow visualization ideas that are known to be effective in this setting [AMM\*07], such as Heatmaps [LMK07], but tailor them to our sailing scenario.

### 2.1. Spatio-temporal visualization

The data visualization community has a taxonomy of visual design for comparing multi-dimensional time-varying data [Gle18]: *Juxtaposition*, showing different objects separately; *Superposition*, overlapping objects in the same space and *Explicit encoding*, encoding relations between objects visually. There are other works that refine this taxonomy by focusing on visual encodings like Javed *et al.* [JME10a] and Correl *et al.* [CAFG12], who compare several techniques: *Line graphs*, *Braided graphs*, *juxtaposed views*, *Horizon graphs* and *Heatmaps*. The last one stands out due to its ability to scale to more variables and its capacity to carry out global tasks. However, displaying large amounts of time-varying data can easily exceed our perceptual capabilities [ED07].

### 2.2. Glyph visualization for sport visualization

A common technique to represent multivariate data is Glyph visualization. Here, data are rendered by a collection of visual objects with a semantic meaning by using metaphors [BKC\*13], allowing intuitive and expressive representations of the data. It has been

used extensively in the data visualization community, with several studies on glyph design guidelines [BKC\*13, MRS\*12, War02, CLP\*13] and applications to spatial-temporal data design studies [SvdWvW14, DTW\*15, CSB\*20, LCP\*12]. However, most of the authors prioritize spatial component rather than temporal aspects. For instance, Duffy and Thiyagalingam [DTW\*15] compare and correlate the multidimensional and time varying data measurement of multiple sperm cells by using Glyphs to encode 20 variables. The authors claim that this representation helps memorization and provides an overview of a large set of spatial measurements.

Glyph representations for sports visualization mostly focuses on *Box-score* or event data [DY20], corresponding to discrete representation of an activity. Glyph encoding, in particular for racket sports, has received a lot of attention [PYHZ14, WLS\*17, WZD\*20, PJHY20]. Polk et al. [PYHZ14] developed a glyph encoding to analyse the point outcome evolution. Even though we can borrow some of these concepts, they tackle a low dimensional set of variables compared to our problem.

### 2.3. Sailing data visualization

Despite there being no specific visual design studies applied to sailing, the sailboat designers have developed a series of visualization adapted to analyse sailing data: To measure performance in sailing, a specific model is used, the Velocity Prediction Programme (VPP). The VPP is an aerodynamic and hydrodynamic model based on predictors of the boat's velocity under different wind angles and speeds. Usually, it is visualized by means of a radial plot as it can be seen in Figure 2a, where the angle encodes the wind angle and the radius represents wind speed. A curve is formed by interpolating between the wind angle and velocity pairs. Boehm et al. [BBDG13] compare the performance of two boats by superposition of their VPP curves. This visualization helps in comparing different performances but it does not give further insight on the reasons behind different performances. Moreover, this technique is not adequate for multivariate information.

### 3. Sailing Background

In sailing regattas, boats race together on a marked circuit. Optimal boat handling is crucial for a fast completion of the circuit. During training sessions, sailors try to find the optimal boat handling to maximize the boat's performance. In our work, we do not consider the variables involved in the setting of the boat (e.g. setting the curvature of the sail) as they are not measured and they are not modified during the exercise. Instead, we focus on the boat handling. Handling a boat involves the use of several mechanisms, where the most important ones are listed here and illustrated in Diagram 2b, and they also correspond to the set of variables used in this work. First, for controlling the direction, the sailor uses a hydrodynamic surface called rudder. Second, with a rope attached to one of the sail's corners, called *clew*, the sailor adjusts the tension on the sail in order to control the acceleration of the boat. An important set of variables defines the boat's orientation as three rotation angles: *heel*, *pitch* and *course over ground* (COG). One of the training goals is to find the optimal handling that maximize the boat's performance under same weather conditions and specific settings.

### 4. Domain Analysis on Training Sessions

After a training session sailors and coaches meet for debriefing, during which they review the last session and try to strengthen the learning objectives of the day. Under ideal weather conditions, the sailors know that the boat will go faster if there is little or no variation of the boat's handling. Notwithstanding, ideal weather conditions are seldom realistic in a real navigation environment, and a sailor has to constantly deal with the influence of external factors. A sailor may move the rudder a lot during an exercise to avoid waves, which might be a better strategy than keeping a straight course, as would be the case under ideal conditions. Hence, identifying the differences in how sailors deal with the weather circumstances and the resulting outcome in terms of speed are objectives of the coaches' analysis. The main task of the *Line-up* exercise is to **compare** the handling of the two boats under practically identical external conditions to **understand** which combination of variables is associated with an increase of speed.

The differences between boats are difficult to evaluate by visual observation from a coaching boat or via videos. On the other hand, sensors on the boat actually provide direct information of the most relevant variables that can be measured. Currently, coaches compare variables individually using aggregated statistics (component D in Figure 1) and raw video visualization. They elaborate a mental model of the situation and provide feedback to the sailors. This procedure neglects the broader context and discards most of the local and temporal details. The *Line-up* exercise was of specific interest for the domain experts, since it is where they see the true potential of using the sensor data at the moment.

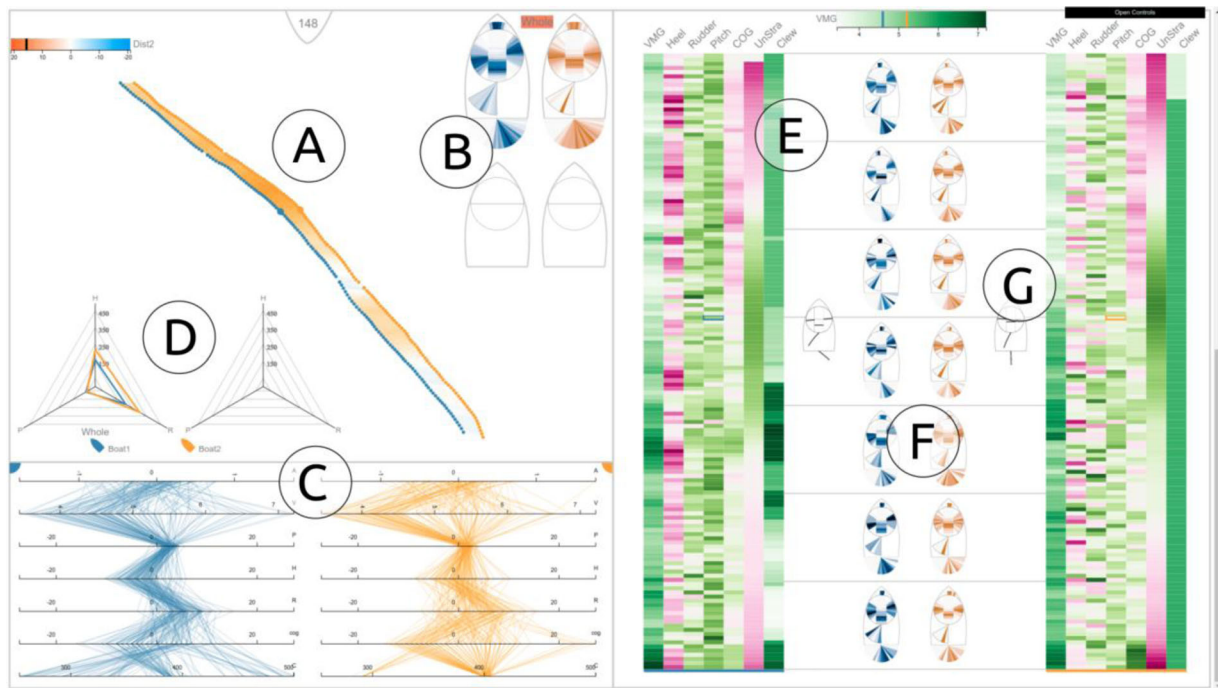
### 5. Data Analysis

Based on a commercial data acquisition system, several sensors with an acquisition frequency of 1 Hz are attached to the boats. The recorded variables are:

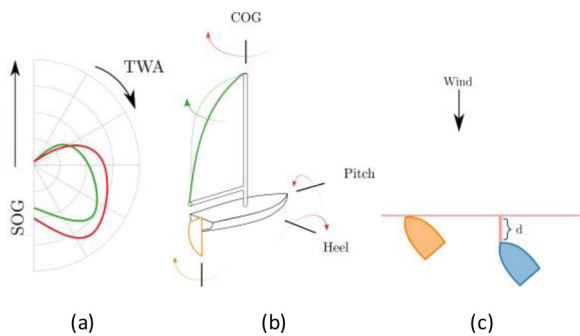
- **Heel angle** via an inclinometer sensor;
- **Pitch angle** via an inclinometer sensor;
- **COG** via a compass;
- **Rudder angle** via a magnetic sensor;
- **Clew load** via a load sensor;
- **Global position** via a global position sensor (GPS).

The only weather measurement provided is the general direction of the wind during the exercise. Current weather measurements or simulations are not available or the resolution is too low to add value.

Starting from these measurements, the sailing team and us derived a complementary new set of measurements that are important for the sailing analysis and are not covered by the used commercial system. The first derived measurements are related to the speed. Using the global position coordinates, we extract the *speed over ground* (SOG) and *velocity made good* (VMG). The latter is an important measure from a sailor's perspective, as it measures the boat's velocity in the direction of the wind and is computed by:  $VMG(t) = SOG(t) * \cos(TWA(t))$ , where true wind angle (TWA) is estimated by the coach through our dashboard. The next derived



**Figure 1:** Main view of ComVis-Sail's dashboard. It incorporates trajectory points of two boats and its Winning lines (A); Summary glyphs of the boat-handling variables. We show two glyphs for each boat, the top row encodes the whole Line-up and the second row the data that is selected through interaction (B), a parallel coordinates plot (C) to explore relationships between variables which is already in use, a radar plot (D) summary statistics of a subset of the variables, an overview of the multi-dimensional data multi-resolution Heatmaps (E), a Summary glyph for the temporal aspects (F) and an instant glyph for individual timestamps (G).



**Figure 2:** (a) VPP diagram for comparison of two models of one sailing boat. (b) Boat diagram: rotation angles in red, clew deformation in green and rudder appendix and its rotation in orange. (c) Measurement of distance between the boats.

measurement is the *distance between the boats*, which is dependent on the wind direction as depicted in Figure 2c. While sailing up-wind, the distance is not measured as the Euclidean distance between the boats. Instead, from the position of the boat that is ahead, a perpendicular line with respect to the wind direction is defined and the distance between the boats is measured as the Euclidean distance of the second boat to this line.

## 6. Design Process Procedure

This project was elaborated during 2 years in close collaboration with two groups of Sailing experts in terms of roles and relation with the developments. The first group consists of one person: a research scientist with a background on Human Movement Science with 4 years of experience in a wide range of scientific projects applied to Sailing, we refer to him as a *Sailing Expert*. He is responsible for giving technical support to professional coaches and sailors. We discussed the goal of the project, its tasks and visual design in weekly meetings. During each meeting, we presented several task/design options and discussed its advantages and disadvantages. First, we discussed the design options in a broad exploratory manner to stimulate the debate and learn more about the situation and requirements. Then, after narrowing down the options, we proceeded to investigate the most effective design. We followed the design methodology proposed by Seldmair *et al.* [SMM12] as guidelines on how to conduct design studies and avoid common pitfalls and Meyer and Fisher [MF18] to structure and refine the user questionnaires.

The second group was formed by two coaches. *Coach1* has 8 years of professional coaching experience while *Coach2* has 3 years. Both coaches have been using the data acquisition system during the last two seasons. These coaches are the end users of our developments. We had an initial evaluation with both of them and three evaluation sessions after training practices with *Coach2*

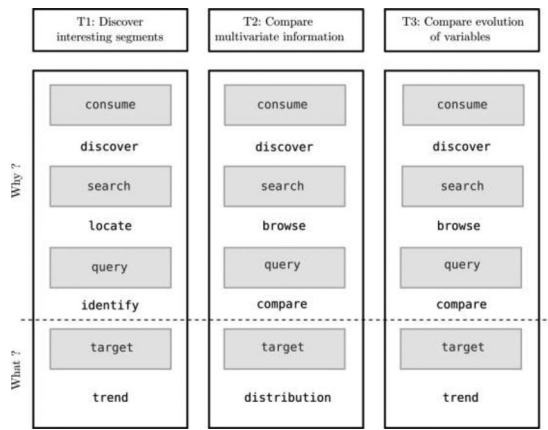


Figure 3: Task abstraction overview.

and multiple sailors. We also had a formal evaluation to discuss the glyph design, which is the main component of our design.

## 7. Task Analysis

After a series of interviews and discussions with the *Sailing Expert*, a set of tasks, following Munzner's design guidelines [Mun09], were elicited. In the following, we use a mono-spaced font when referencing this typology. The main goal is to visually compare the multivariate spatial-temporal data collected from the sensors on the boats during a *Line-up*. The aim of this work is to allow coaches to explore the data looking for interesting or unexpected behaviour that may affect the boat speed. To do so, our main question *what behaviour leads to one boat going faster than the other?* can be divided into a two-part question. This division was identified during the first iteration of interviews as coaches considered an effective workflow to first know *which* interval is producing interesting or unexpected patterns and then to analyse whether these differences can be explained by the boat handling (**why**):

1. **When?** *In which time interval an interesting or unexpected behaviour may affect the boat speed?*
2. **Why?** *For these intervals, what makes one boat faster than the other?*

We transform our questions into tasks:

- **T1:** Discover interesting segments (*when?*),
- **T2:** Compare multivariate information (*why?*), and
- **T3:** Compare evolution of variables (*why?*).

An overview of the identified tasks and corresponding actions and targets are shown in Figure 3.

### 7.1. T1: Discover interesting segments

Discover interesting or unexpected behaviour appears during the exploration of the data, by exploring how the distance between the boats evolve or unexpected patterns shown in the boat handling variables.

**Abstraction.** During **T1**, the users discover through comparison, locates and identifies segments of the *Line-up*. The target is the trend of the comparison between the boats.

### 7.2. T2: Compare multivariate information

Even experienced coaches cannot predict the precise performance based on a given combination of boat handling variables. Thus, our visual design should allow for **discovering** the patterns of variables. This should facilitate the generation of a hypothesis on the influence of the combination of variables in relation to performance. For this task, the temporal aspect is disregarded and the focus is on the combination and the instant multi-relationships. In order to allow for **exploration** to locate successful combinations, the following sub-tasks were identified:

- **T2a:** Here, the time component is disregarded and the focus is on comparing two 1-dimensional **distributions** of multiple quantitative variables independently.
- **T2b:** Discover the combination of measured values that leads to better performance. This task focuses on how to identify variable *relationships* between multivariate information and compare them between boats.

**Abstraction.** During **T2**, the users discover, browse and compare the boat handling variables. The target is the distribution of the multivariate information and the distribution of the *relations* between the variables.

### 7.3. T3: Compare evolution of variables

Taking time into consideration, it is important to **compare** how successful combinations of variables evolve. Moreover, it should allow the user to explore the cause-effects relations.

**Abstraction.** During **T3**, the users discover, browse and compare the boat handling variables. The target is the trend of the multiple variables.

## 8. Visual Design

In this section, we present the design process of ComVis-Sail (see Figure 1), it supports the tasks discussed in Section 7. This *Line-up* analysis is done in several steps. First, one discovers which boat is performing better. Then, one will investigate where those differences of performance are coming from by comparing boat handling. The user will find which boat is ahead by looking at the Trajectory Figure 1A, then, explore the differences in performance by moving from the Summary views Figure 1(B, C and D) to Temporal views of the data Figure 1(E and F). With interaction mechanism, the user is able to select interesting behaviours based on the Trajectory & Winning lines, Figure 1A, and Heatmaps, Figure 1E, or even specific boat handling configurations with the Parallel Coordinates Plots (PCPs) Figure 1C. A selection in one view is automatically transferred to all other views.

For a clearer explanation of our design, we group the components according to the data abstraction they provide and the intended workflow (Table 1):

**Table 1:** Components of the dashboard and their associated tasks. Refer to Figure 1 for the labels.

Label	Name	Group	Task
A	Trajectory & Winning lines	Trajectory & Winning	T1
B	Summary Glyph	Summary view	T2a
C	Parallel Coordinates Plot	Summary view	T2b
D	Radar Plot	Summary view	T2
F	Instant Glyph	Temporal view	T3
E	Heatmaps	Temporal view	T3

We developed an in-between prototype, mainly based on a line chart describing the distance between two boats and a Heatmaps to visualize the boat handling variables for hypothesis generation. We then performed a structured evaluation of this initial prototype with the two coaches, which resulted in multiple insights and lessons learned. These lessons are the starting point of our current design and they are described in this section. The main issue was regarding the Heatmaps, since it is a generic representation, it lacked semantics and made identification and retrieving values hard. Nevertheless, it was deemed important to have an overview of the variables. Based on these observations, we decided to design a glyph to encode the variables related to boat handling. Before we dive into the main components of the dashboard, we explain the glyph design and evaluation processes.

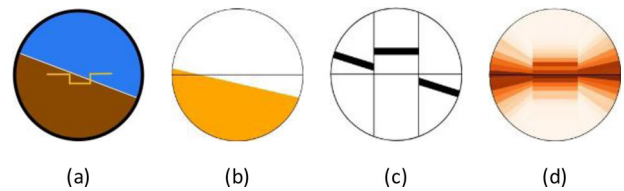
### 8.1. Boat glyph design

The glyph is considered for individual data points, as well as to represent a summary of a period of time. The glyph emerged as a valid visual encoding to facilitate interpretation and add the lacking domain context to the variables. Initially, the glyph representation was planned to only complement the Heatmaps and support **T3** by encoding multi-valued information at each time step. After a few iterations with the sailor experts, it became clear that glyphs could also be used as a *Summary* option and support **T2a** by encoding the distribution of the variables.

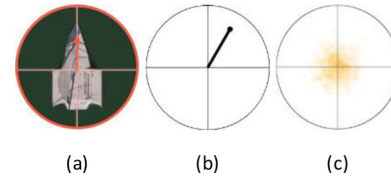
We followed the guidelines proposed by Borgo *et al.* [BKC\*13] and Ward [War08] as well as the lessons learnt in other related designs studies 2.2. During the iterative process with the domain experts, several designs were developed and discussed. The designs were presented with a slider per variable so the *Sailing expert* could explore different variable setting. After several iterations, we carried out an evaluation of the glyph with the two coaches involved in the project to make an initial selection.

The encoded boat handling variables are: *Rudder*, *Heel*, *Pitch* and *Clew*. Other variables, like the *VMG*, *Straightness* and *COG* are considered external as they are a consequence of the boat handling variables and, conceptually, can be better explained through the other components. All these boat handling variables have the same importance for the domain expert.

The cornerstone of the design was the encoding of the rotation angles (*Heel* and *Pitch*) and the *Clew* variable. For the rotation angles, we mainly iterated around two designs. The first, called *Horizon*, is



**Figure 4:** Evolution of the glyph Horizon encoding (a) airplane artificial horizon instrument (b) instant first design using the metaphor of (a), (c) final design with separation of heel and pitch, (d) Horizon summary glyph.



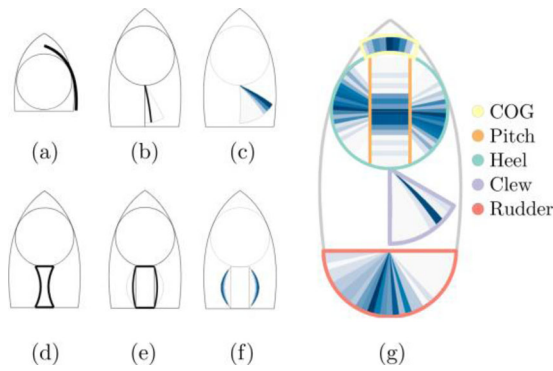
**Figure 5:** Evolution of the glyph Mast encoding (a) image of a boat as seen from above with Mast encoding overlay, the red circle represents the top of the mast (b) instant design using the metaphor of (a), and (c) Mast summary glyph.

inspired on the artificial horizon instrument on planes (Figure 4a), as it represents the plane's relative orientation to the earth and mimics the relationship of the aircraft relative to the actual horizon. The typical encoding is composed of a circle with a fixed central horizontal chord representing the horizon, and another chord, whose rotation represents the *Roll* (*Heel* on a boat) and its vertical displacement the *Pitch* (Figure 4b). Nevertheless, we realized that, as the visual marks are not completely separable, the angles are difficult to retrieve. This was confirmed by the two coaches although they remarked that the horizon line idea was intuitive and suitable for our problem. We then decided to encode the *Heel* independently as a rotation of the central chord, and the *Pitch* as a translation from the horizon (Figure 4c).

Our second glyph encoding, dubbed *Mast*, was inspired by a glyph to represent surface orientations [Ste81] that we adapted to our sailing scenario. It uses the metaphor of a boat viewed from the top, as illustrated in Figure 5b. The 3D orientation of the mast changes with the *Heel* and *Pitch*. We represent this rotation by projecting the top of the mast onto the circle in the glyph. More specifically, the  $X$  and  $Y$  coordinates of this point are expressed in spherical coordinates:  $X = r * \cos(\text{Heel}) * \cos(\text{Pitch})$  and  $Y = r * \sin(\text{Pitch}) * \cos(\text{Heel})$  here  $r$  is the radius of the circle.

We add a top view boat silhouette so we can represent semantically the boat entity. The *Mast* design matches the metaphor used to represent the boat entity. Therefore, the overall form of the glyph resembles a boat (Figure 2b). Conversely, the *Horizon* metaphor assumes the viewpoint of the sailor, that is, from inside the boat and looking forward.

To represent the *Rudder*, we added a line segment at the back of the glyph entity. The orientation of the line depicts the *Rudder* angle, which resembles a real *Rudder* from the top. It can be seen in Figure 1G.



**Figure 6:** Evolution of the glyph design for the Clew encoding, first row using the Sail metaphor, bottom row using the Force metaphor. (a) Initial Sail design, (b) final instant Sail design, (c) Sail summary glyph. (d) Initial Force design, (e) final instant Force design, (f) Force summary glyph and (g) the Summary Glyph with labelled components.

Finally, we also considered variations for the *Clew* variable that measures the load on the external edge of the main sail. A *Clew* variation produces a rotation and a deformation on the top part of the sail. Initially, we proposed a top-view representation where the load was mapped to the rotation of a curve at the front of the boat (Figure 6a). There were two concerns: first, given the location and the length it resembles a *gennaker*, as pointed out by the Sailing expert, a type of sail hoisted during *downwind* sailing mode. Since this specific sail was not captured by the sensors, it might induce confusion. The second concern regarded the design itself, since a rotation does not properly represent the concept of a load or tension. To overcome these issues, we developed two solutions. The first, called *Sail* design (Figure 6b), keeps the *Sail* concept but reduces the length and places it on the back of the circumference, resembling more a mainsail. Even though it still encodes the load as a rotation, it now resembles the actual rotation experienced by the top part of the sail. During the midpoint evaluation, the coaches agreed that this design was an appropriated metaphor of the *Clew* load. Our second design is called *Force* (Figure 6e). We also placed it at the back of the circumference, representing the *Clew* as a rectangle that is deformed as the load increases. Initially, the rectangle would deform inwards (Figure 6d), but one coach observed that it should, instead, deform outwards as it is the process experienced by the top part of the sail when it gets loaded. For both designs, we add an enclosure so the maximum and minimum references are clear.

The data values are mapped linearly to their channel, some data values are small, e.g. the *Rudder* sensor usually produces values between  $10^\circ$  and  $-10^\circ$ , we add an exaggeration controlled by the user parameter to modify the slope of that linear mapping.

Comparisons are based on juxtaposition of glyphs as coaches make comparisons by looking at the variables of the boats separately. Other comparison options, like overlaying or deriving some mix encoding, would make it hard to retrieve the values, as it involves an inversion process.

We also extended the instant glyph to support **T2a** by encoding the distribution of the variables, that is, with a *Summary* design. For

the rotation angles, on the *Horizon*, we encode the distribution of the variables as histograms, as shown in Figure 4d. Bins for the *Heel* are created as several arcs around the centre that are filled with a quantitative colour scale to represent the probability of the distribution at each bin. We apply the same idea for the *Pitch* but with rectangles translated from the horizon. Similar for the *Mast*, we overlay the projections of multiple points using transparency to indicate the density, as shown in Figure 4d. Finally, for the *Clew* options, we extended the metaphors by creating geometric bins.

## 8.2. Glyph evaluation

At first, it was unclear which glyph option would work best, therefore, we developed an evaluation to test their effectiveness. After iterating the design with the *Sailing Expert*, we did a midterm evaluation with the two coaches considering the rotations for a version of the *Horizon* design without the angle separation and the *Mast* design. For the *Clew* variable, we test the deformation concept <https://forms.gle/K4uSNMBHWh8D2csa8>.

With the *Mast* and *Horizon* designs ready, we evaluated their efficacy: <https://glyphevaluation.herokuapp.com/>. It was planned as an online, self-contained, interactive and cross-user evaluation. In order to reinforce the understanding of the design, we used an interactive version of the glyphs. The objective was to understand which design works best in our context by comparing the boat variables. We presented several exercises of basic sub-tasks for **T3**, the tasks were generalized allowing us to evaluate the effectiveness of the encoding with more users, even without sailing background. The evaluation form had the following blocks:

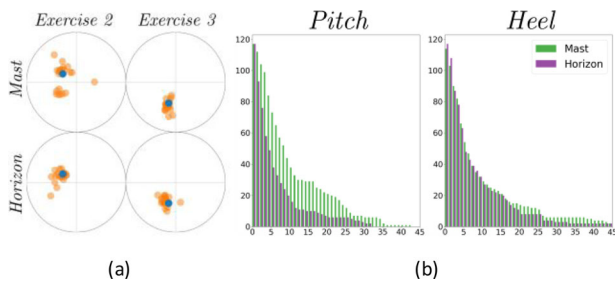
- **Instant single glyph assessment:** the participant has to retrieve the value from the instant glyph encoding.
- **Comparison assessment:** Given two glyphs of the same design the participants compares variables.
- **Summary glyph assessment:** Given a sequence of the instant version of glyph and two *Summary glyph*, the participant has to choose which *Summary glyph* matches the sequence.

We measured three aspects: accuracy, confidence in their answer and elapsed time between views. We finalized each design-task block with an open question about the subjective preferences.

We gathered evaluations from 32 participants with the following distribution: 17 visualization researchers with no sailing experience, two participants did not specify their role and 13 with a sailing background. This last group was composed of six sailors with the following years of professional sailing experience: 4,8,10,14,14,25. Five coaches with the following years of professional coaching experience: 2,2,3,5,9, and finally two sailing managers involved in the design process.

For the *Instant single assessment*, multiple questions with one glyph showed a quantity, the participant through an interactive mechanism had to retrieve its value. For the *Comparison assessment* task, two glyphs with different values were placed next to each other and the participant had to answer for each variable, which one had a higher value. In these two blocks, the shown quantity alternates between the design options, using a random value assignment. Finally, for the *Summary glyph assessment*, an alternating se-





**Figure 7:** Error plots in Block 1: (a) distribution of answers using the Mast angle encoding, top row shows the answers for Mast, and bottom row the Horizon design of two different representatives exercises. (b) Shows the comparison of the absolute error per variable in a cumulative histogram.

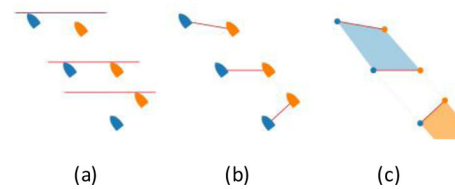
quence of instant designs was presented drawn from a random distribution and the user had to choose the *Summary* that matched the sequence.

For the *Instant single assessment*, the distribution of answers per design of two exercise can be seen in Figure 7a (each row is a design). We removed two evaluations as the participants consistently confused the sign of the angles or misunderstood more than four exercises. For the *Mast* design, we see a consistent underestimation of the angles and spread of values, while for the *Horizon* design, there is a persistent error but they are more compact, which is a consistent pattern in other exercises as well. This might be due to the non-linearity of the encoding and the fact that the user has to deal with two variables at the same time. In Figure 7b, the absolute error per design and variable is shown. It can be observed that for the *Horizon* design, the *Pitch* is smaller. In both designs, the *Pitch* has a similar encoding, but with the *Mast*, the user has to deal with two angles at the same time. On the other hand for the *Heel* error, the *Mast* design produces a larger error. The error on the *Horizon* design is mainly because there is a persistent error, but the results are closer together.

For the *Comparison assessment*, both designs had similar results for the *Pitch*, but the *Horizon* outperformed *Mast* regarding the *Heel*. There was no significant difference on elapsed time and confidence, and both designs had similar accuracy results in the comparison task. Finally, for the *Clew* variable, the *Sail* outperformed the *Force* design.

In the open answers, independently of background, the participants noted that it was easier to work with the *Horizon* design as they could deal with the angles separately. It was also perceived as more accurate. For the *Mast* design, most of them struggled to work with both angles simultaneously. The sailing experienced participants considered that there is no advantage of one design over the other metaphorically wise. For the *Clew*, the *Sail* design was considered more representative of the *Clew* concept by 23 out of total 31.

Regarding the *Summary* version, one notable difference between the two designs is that the *Mast* summary allows to explore the correlation between the *Heel* and *Pitch* values, however, this task was not identified as important by the testers involved in the evaluation.



**Figure 8:** Distance encoding for three different situations: blue boat ahead (top), draw (middle), orange boat ahead (bottom). (a) Winning lines as a perpendicular segment to the wind direction. (b) Winning lines as connecting segments between the boats. (c) Distance between the boats represented as filled parallelograms with diverging colour scale.

The overall conclusions of the evaluation show a slight preference for the *Horizon* glyph. However, since there are no conclusive results, the angle encoding can be selected while using the dashboard. For the *Clew*, there is a strong preference for the *Sail* design. For more detailed results, please see the Supplementary material.

After describing the glyph design and evaluation, we will continue describing the overall visual design.

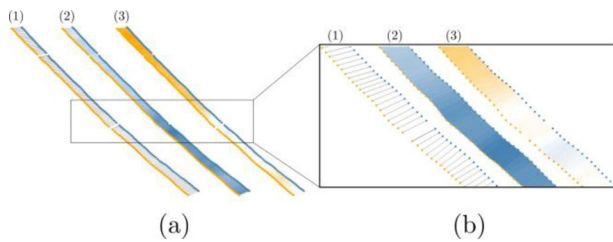
### 8.3. Trajectory and winning lines

On our initial design, we tackled **T1**, *Discover interesting segments*, by using a line chart of the distance between the boats. Although it can effectively convey the distance, according to the coaches it lacks contextualization. Sailors are used to reasoning about the distance between boats within a trajectory. Moreover, seeing the trajectories helps them to remember what happened at that moment. In addition, sailors are used to seeing the trajectory in relation to the wind. When explaining some concept, coaches typically draw the wind coming from the top part of the board and the boat trajectory rotated according to the TWA (Section 3). Therefore, we followed this procedure as shown in Figure 1.

The representation of the Winning lines following the definition of distance between boats from Section 5 is illustrated in Figure 8a. However, when scaled up to multiple data points (usually we deal with 120–240 points), it is difficult to establish the correspondences between the front line and the corresponding second boat. Therefore, we draw a connecting line between the boats instead, where the angle between the line and the virtual horizontal line indicates which boat is ahead at each instant, as depicted in Figure 8b.

In the case of a long *Line-up*, more than 250 points, and boats sailing close together, the *Winning lines* become cluttered. Thus, we add an alternative to fill in the parallelograms formed by two consecutive *Winning lines* with an orange-steelblue diverging colour map, encoding the distance between the boats (Figure 8c). We further added a magnifying lens mechanism to overcome cluttering. However, it was discarded in a later phase as it does not preserve the angles, which was disturbing according to the *Sailing expert*.

Another consideration is that the starting alignment between the boat is not exact. Usually, one boat starts a bit ahead of the other and, consequently, this difference is carried to the *Winning lines* filled



**Figure 9:** Trajectory and Winning lines from real data, (a) the entire dataset, and (b) zooming in the middle part. We also show: (1) just the Winning lines, (2) coloured lines encoding absolute distance between the boats and (3) coloured lines encoding balanced start.

colour. As one of the coaches pointed out during the evaluation, if one boat starts ahead, its colour fading is consequence of the other boat's better performance. Instead, they would prefer to observe the rising of the colour of the boat that is performing better. Therefore, we set the starting distance to zero even if the first winning line is not perfectly horizontal. We can see these distance difference on the rectangular and zoomed-in area of Figure 9. Moreover, by default, the trajectory points show the boat identity, but on demand, it can be switched to colour-scales representing the *VMG* or the *COG*. This is useful to give a spatial context to this variables.

#### 8.4. Summary view on boat handling

Once coaches know which boat performed better, they are interested in knowing which combination of variables causes a difference of speed. The first approach is at a summary level, which gives an initial direction on where to search with further detail. For some cases, the summary can be enough to discover the difference and no further analysis is needed. To support **T2**, we have two components, the *Summary Glyphs* and the PCP that will be explained next. These components are marked with B and C, respectively, in Figure 1.

##### 8.4.1. Parallel coordinates plot

Since *Summary glyphs* treat variables separately, it is not possible to establish the correlation between the variables, which is also of interest to the coaches. For instance, one important relation is between the *Rudder* and the *Heel*, as they are the mainly responsible for the boat's stability, especially during wavy conditions. Therefore, we use the well-known PCP [ID90] to address task **T2b**. We add *Acceleration* to enable some local temporal constancy between the polylines, *acceleration* is computed as the difference between *VMG*. The initial order was defined by our collaborators, but we treat all variables as equally important and a dragging mechanism allows reordering the axis. For each instant time, we render a poly-line that passes through the horizontal variable axes. The opacity and diffusion of the poly-lines are used to control the amount of detail and avoid clutter. Furthermore, the distribution of the relations pops up [HW13], see Figure 11b.

##### 8.4.2. Radar plot

We have included the only visual analysis idiom that was previously used by the sailor experts; the *Radar plot* (Figure 1(D)). Hereby, the

coaches can link new components and tasks to past analysis. For the three variables of interest, *Heel*, *Pitch* and *Rudder*, it uses an aggregated measurement of each signal, called *travel distance*. It is the summation of the absolute value of the gradient of each variable. Under ideal conditions, based on the sailing theory, the least variations on the variables related with the boat's parts in contact with the water, such as the rudder, will produce the best performance. Encoding the aggregated measurements in this way enables a summarized comparison of the variables but misses all aspects of variability in the data, which is captured by the PCPs and other views.

#### 8.5. Temporal view on boat handling

Task **T3** consists of comparing the variables' evolution. We use a Multi-resolution Heatmap arrangement to show the temporal evolution. For each boat, a matrix is created where a column represents a variable and a row represents a specific timestamp. A quantitative colour-scale is used for the value of each time-varying channel. The multi-resolution term comes from the possibility by the user to control the amount of temporal resolution. Among the different options to visualize multivariate data [JME10b], our choice was based on the following requirements: a global view of the whole sequence, highlighting the relation of local changes between variables, and avoiding clutter when adding more dimensions.

As mentioned in Section 8, the evaluation of our first prototype showed a lack of intuition when it comes to interpretation of the variables with Heatmaps. Therefore, we complement it with glyphs (see F in Figure 1). In this way, we keep the advantages of each technique, glyphs are intuitive but require space while Heatmaps allow us to show more temporal continuity [LMK07]. *Summary glyphs* are used to encode the distribution within temporal blocks while hovering over a cell of the Heatmaps with the mouse cursor shows an Instant glyph to reveal details.

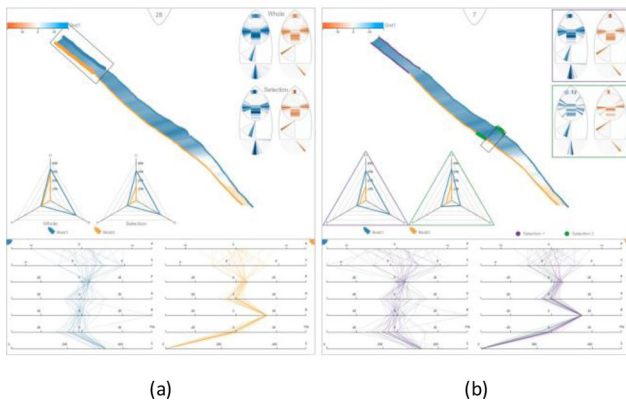
#### 8.6. Interaction mechanisms

In this subsection, we explain the dashboard's interaction mechanisms. The main interactions are based on the trajectory and PCP and are coordinated to other views.

##### 8.6.1. Selecting interesting behaviours

We add a data selection mechanism (*details on demand*) based on a *Lens* without distortion and modifiable size (see Figure 10a). This lens is draggable and coordinated with the other components. This selection applies on the trajectory lines and on the heatmaps. Both selections are linked. The other components are updated to only consider the selection. We duplicate the *Summary Glyphs* to allow comparing the whole *Line-up* against the selection. This interaction mechanism also adds temporal information to the *PCPs* component.

Moreover, it is interesting to compare two temporal blocks such as the beginning and end of the exercise, or low against high speed blocks (Figure 10b). We also concluded that comparing more than two groups simultaneously does not bring additional information.



**Figure 10:** Interaction mechanisms on the trajectory. (a) Selection on the trajectory, and (b) grouping on the trajectory.

### 8.6.2. Selection on parallel coordinates

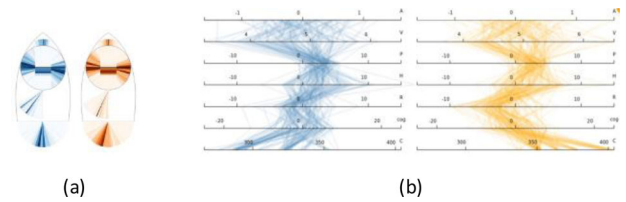
In the PCP, the horizontal axes present a numeric scale that enables the user to make queries to the data, for instance, by specifying a specific range of values on one of the axes. We implement this query by a brushing mechanism on each axis and colouring the polylines within the selection and removing the rest. In case of selection on multiple axis, only the polylines that fall exclusively in all ranges are shown. In the initial design iterations, the *Sailing expert* indicated that it is interesting to explore the combination of variables that are linked to positive acceleration and high speed (values on the high end of the VMG axis). The points of a selection are also highlighted on the *Trajectory lines*. Another evolution of this interaction mechanism is to compare a group of selections, for instance, allowing comparison between high/low speed acceleration. In this case, we attribute different colours to the two groups.

## 9. Case Study

We evaluate our prototype through a set of sessions with the two coaches and sailors. They were not involved in the dashboard design but are active users of the data acquisition system, their expertise is described in Section 6. Both coaches also participated in the evaluation of the first prototype. We organized two types of evaluation phases. The first consisted of a presentation of the tool followed by the analysis of a series of Line-ups, and finalizing with a set of qualitative questions. In this phase, we intervene very often to ask what they saw on the different components. The next phase was the evaluation, which consisted of three sessions with a coach and the sailors during debriefing after a training session.

### 9.1. Phase 1

After explaining the tool, we analysed together a Line-up. During training, there were low wind conditions and small but frequent waves. By using the *Radar Plot* described in Section 8.4.2 and videos recorded by the coach during the exercise, they concluded that the key point of that day was to try to build momentum in order to overcome the waves, or to try to avoid them in order to not lose speed. This can be achieved by a proper combination of a centred



**Figure 11:** Summary Glyph of two boats (a): The coaches observe that Boat2 orange has more variation and an un-centred distribution of the rudder. PCP plot (b): Coaches point out that the PCP structure of Boat2 shows a clearer relationship between rudder and heel that might contribute to its success.

*Heel* angle and correct movements with the *Rudder* and low values of *Pitch*.

Next, we describe their comments and findings when using our dashboard.

#### 9.1.1. Identify different speed segments

From the *Trajectory and Winning lines*, both coaches could describe the progression of the distance between the boats. During the first half of the exercise, both boats alternate on assuming the lead, while in the second half, *Boat1* loses distance. This change of the distance can be seen in Figure 9. The coloured version was easier to understand. With this view, they would be ‘able to explain it to the sailors’, in reference to the difference in performance between the boats. One coach suggested to enlarge the *trajectory and Winning lines* as ‘the lines helps us to remember what the exercise was like. Further analysis comes after this. After this, all the data makes more sense’.

#### 9.1.2. Compare combinations of variables

After analysing the boats’ progression, the coaches looked at the *Summary Horizon glyphs* (Figure 11a). The first comment was based on the comparison of the shape of the distributions and deviation from the centre, especially in regard to *Heel and Rudder*. One coach mentioned: ‘*Boat2 is going faster but its variation and un-centred Heel and Rudder goes against sailing theory*’. However, he then commented that for this wavy condition, it might be the key factor that led to better performance.

Finally, they used the PCP. At first, *Coach1* said that rather than seeing the polylines at each instance, one should show the speed connected to one second before. He argues that the current speed is a consequence of past actions. However, we pointed out that we add the acceleration variable to have this time integration and the temporal resolution is too low to capture the boat’s dynamics, he was satisfied with this point. *Coach2* found it interesting that *Boat2* on the *Summary Glyph* has more variation and un-centred values, but on the PCP (Figure 11b), it has more clear polylines, especially between the *Rudder* and *Heel*. He commented that, even though one can observe a wider distribution, the strong correlation shows a better coordination between those variables, and it might be the cause of the boat’s success. They are not used to working with all the variables, but they would like to work with the ones that they believe

have more importance after the training session and explore them in more detail.

## 9.2. Phase 2

As stated before, in this second phase, we run experiments to observe how the users extract information from the dashboard. Typically, they observed some boat/sailor behaviour during the training session and, by analysing the data with the dashboard, they arrive at conclusions to apply in future training sessions. We used the same acquisition system. We worked with *Coach2* whose experience is described in Section 6 and a group of sailors that have been sailing with this boat during the last 3 years. Usually, the analysis follows the same pattern: they start by setting the *Trajectory lines* with the coloured distance, they inspect the *Summary Glyphs* and then explore in more detail the temporal aspects, while making different selections. Next we describe their findings.

### 9.2.1. Session 2

This session took place in a lake, which means that the boats were not affected by the current. The temperature was low so the sailors were not comfortable sailing during the training session. The wind was strong and gusty.

During sailing, the sailor on Boat1 (Blue) was slower during the exercises. The sailor pointed out that he struggled to manage the boat and to reach higher speed due to a high pressure on the *Rudder*, he identified this as the main cause for the loss of performance. He could not relieve this effect with other handling mechanism to reach a higher speed. This effect is well known in sailing, it is called *Weather helm*, and consists of the tendency of the boat to rotate towards the wind (reduce the TWA) and consequently lose speed. The sailor tries to compensate the rotation by using the *Rudder* to stay on the intended course. However, by strongly using the *Rudder*, a drag is created that slows the boat down. This effect can be neutralized by sailing the boat with less *Heel* or reducing the sail area, however, the extent of each factor and its interrelation is difficult to deduce. This was the starting hypothesis of the analysis for sailor and coach.

Figure 1 is the view of the dashboard for this exercise. By looking at the dominant orange colour in the *Trajectory and Winning lines*, they concluded that Boat2 was faster. From the *Summary glyphs* (Figure 1(B)), they highlighted that the *Clew* values had similar peak values but Boat1 had more variation. On the *Rudder*, Boat1 had skewed values. Regarding the *Heel*, Boat1 had too much leeward *Heel*, which means, heel caused by the wind. The coach then concluded that Boat1 had more stable *Heel* and *Pitch* than Boat2. Next, they inspected the *Summary Glyphs* with the temporal arrangement (Figure 1(F)) and realized that for Boat1, there was a relation between the high *Clew* and unstable *Heel* which raised the question: 'When the clew enters, do we get more Rudder or more Heel?'. To answer this question, we proposed him to select the region on the Heatmaps where there is a transition from low to high *Clew* and observe the *Summary glyph* and *PCPs*. However, it only allows to select one specific time range at a time. He struggled to remember multiple selections, so he could not answer the question. He would like to be able to do multiple group selection.

After observing the variation on the *Clew* on different components of the dashboard and its relation with the other variables, the coach concluded the analysis by saying that Boat1 was moving the control of the sail (variation on the *Clew*) and he did not find the right amount of pressure on the sail. That led to an unstable boat and a higher pressure on the *Rudder* and, consequently, Boat1 was unable to reach a higher speed.

### 9.2.2. Session 3

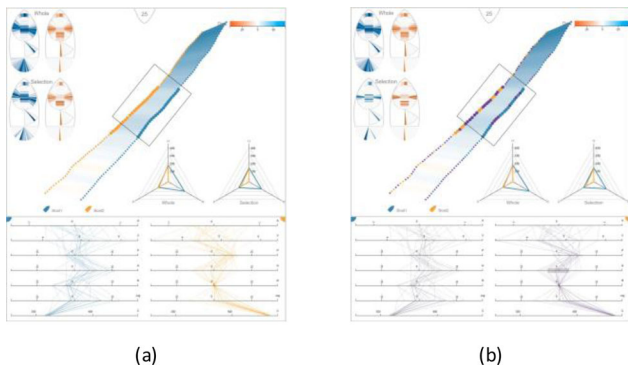
This session took place in the ocean and with mild temperature. The waves were high but with long wave length, so it did not affect much the sailing practice.

Figure 10 shows the dataset and the interactions performed by the coach. During the third session, the *Rudder* and *Clew* sensors from Boat2 did not work correctly and could not be used during the analysis. The coach already analysed the data before the debriefing and when the whole group gathered, he went directly to points he considered interesting. He set the trajectory lines with the colour version, this time Boat1 was ahead of the whole run. He started the analysis by looking at the Heatmaps, specifically focusing on the VMG variable of each boat. He made a selection and when asked for the reason of making that selection he replied: 'I was looking for a high VMG, consistent and long, Boat1 was the quickest, I want to know if there is something different here'. Within the selection, he focused on the *Summary Glyph* and *Radar Plot* of the selection and the whole *Line-up*, based on this components, he said: 'Boat1 has more precise bow down (negative Pitch), neutral Rudder' while 'When [Boat2] heels, the bow goes down too much, that caused a loss of speed'. As the *Clew* sensor was not available, he checked the sail configuration on the video which, apparently, had too much pressure, creating a more unstable platform (variation on the *Heel* and *Pitch*). Then he moved to the selection on the Heatmaps to look for the same pattern on the *Summary Glyph* that corresponded to the previous selection, i.e. high and consistent VMG. He considered that there was a similar pattern near the end of the exercise, and told the sailors that that was the target setting for those conditions.

When they finalized the analysis, we pointed out that on the *Trajectory and Winning lines*, while one colour is dominant, there are some variations, meaning that the distance between the boats varies. They agreed and checked more carefully and made two groups on the trajectory. One near the end that they had already previously discussed, and the second covered the part, where the colour reached the darkest shade, indicating the largest distance between the boats. They said that the momentary gain of distance of one boat is potentially linked to a wind change and the boat trying to turn closer to the wind to increase the VMG, however it is not long enough to reach a conclusion.

### 9.2.3. Session 4

In this session, the wind angle was frequently shifting. The sailors from Boat2 wanted to know how to handle the boat in order to anticipate the wind changing moments. In addition, they want to maintain an optimal compromise between *TWA* and *SOG* during the wind changes. As illustrated in Figure 2a, if the boat has a small *TWA*, it



**Figure 12:** Different selections made by the coach: (a) selection on the middle part of the trajectory. (b) Selection on the middle part of the trajectory and middle Heel values with the PCPs.

will gain upper position, but it will lose *SOG*. Conversely, if the boat has a large *TWA*, it will not gain upper position but it will gain *SOG*. The goal is to keep an optimal angle while the wind changes direction. To anticipate for these situations, the sailors identified having a strong clew tension and a balanced *Heel* as the goal.

They started the analysis with the *Trajectory and Winning lines* with the coloured version, as it can be seen in Figure 12a. They discard the last third as another boat without sensors disturbed them. The boats were equal until the half of the exercise, then Boat1 overtook the other one. They continued describing the summary glyph (Figure 12a). The boats differed on how they tackled this exercise, Boat1 decided to have a low *Clew* tension and high *Heel* to the right, while Boat2 decided to have a high *Clew* tension and low *Heel*. After that, they checked the values of the summary glyph with temporal setting and the Heatmap. The coach compared and described how many *bumps* there were on the evolution of the *Heel* and *Pitch* variables visible in the Heatmap. He wanted to have smoother transition between the values. To finalize with the Heatmaps, the coach told them that Boat2 had too much tension, he thought a value in between the tension of the boats would be ideal.

After having a general idea, he focused on the middle part of the trajectory line, where Boat1 increased the distance and maintained it, as shown in Figure 12a. The coach compared the summary glyphs of the selection against the whole exercise. The coach described that the *Rudder* and *Heel* of Boat1 had narrower values in the selection than during the whole exercise, pointing out that that was what they will have to aim for. Even if the *Heel* and *Rudder* are not centred, they are good for these conditions.

Finally, we suggested to use the PCP to look for patterns that are linked with a high speed and positive acceleration. The pattern that this selection showed on the summary glyphs was linked to the boats being hit by a wind gust, so not a consequence of the boat handling. But the coach asked to see places where the *Heel* values were close to central values. On the middle part of the trajectory, this interaction can be seen in Figure 12b. The Summary Glyphs of the selection reinforced the previous statement regarding the combinations of the values, what the coach considered the optimal conditions for that day.

### 9.3. Expert feedback

We also collected qualitative feedback from the coaches. In general, they agreed that the structure of the task/visual design helps them to analyse the *Line-up*. Transitioning between summary views to more detail with the temporal components was specifically valued as it enables going deeper into their analysis when needed. They agreed that they can elaborate on the winning reasons for the exercise. One coach would additionally like to have a way to contrast the knowledge extracted from each *Line-up* with the others from the same training session, without going through them one by one. Nevertheless, both coaches confirmed that it fits within their working pipeline. They would adopt ComVis-Sail not only because it helps them to extract new information, but also because it saves time in regards to their current video-based tool. Still, having access to the video footage from inside the tool is considered an interesting addition for the future.

It also has proven helpful to communicate the results and explain the concepts to the sailors. The tool then serves as a way to confirm the hypothesis they have in mind. It helps to have a better picture of the sailing boats' performance, combinations of variables and their evolution over time. The sailors also added that usage of the data and the dashboard helped them to learn more about their boat and how the other boat was handled, as they are not always aware of all values of all variables.

### 9.4. Lessons learned

We created the different components of ComVis according to our task analysis and with an intended workflow, during the sessions, the coach altered the workflow according to their needs. He combined different selection mechanisms at the same time, as in Section 9.2.3, where he used the selection on the trajectory and then the selection via the PCP. There were extra tasks that were observed during the sessions, for instance, during the analysis sessions, we observed that besides data analysis, the coach wanted to communicate and teach concepts based on the data. With his fingers selected certain parts of the dashboard or made drawings. These tasks are not supported by the current version of the dashboard.

In terms of components, most of the components were easy to understand, for instance, glyph metaphors did not pose any problems for first-time viewers and they were immediately able to reason with them. Regarding the usage of the Summary glyphs, they did not notice the exaggeration of its values, which suggests that they are interested in the shape of the distribution rather than actual values. Still, upon further enquiry, they stated that they would like to see the real values as well at some point.

During the analysis session, *Coach2* said that he wanted to see correlation between several variables. However, he struggled with the PCPs layout, the horizontal arrangement of the axis was difficult for him to interpret. He still used them to make selections, as the axis range for individual variables is easy to interact with, but visually explored the selection on the Summary glyph. One possible solution is to only show a subset of variables. Finally, the use of colour on the trajectory lines helped to analyse them but it simplified the message since, during the sessions, they only considered the dominant colour. It was after we asked them to look more

carefully to perceive the colour variations, where they notice them and perform a further analysis. It remains challenging to design perceptually adequate colour maps that at the same time preserve adequate semantic meaning and would not be confusing to the user.

## 10. Conclusion

In this work, we presented ComVis-Sail a visual analysis tool for sailing training exercises. Coaches and sailors can debrief training sessions using sensor measurements from their boats, with the final goal of reinforcing their technique. Our visual design aims at facilitating uncovering the reasons behind superior boat performance. To the extent of our knowledge, this is the first visual analysis design for sailing coaching.

Glyph design is a central aspect of our tool. The glyph represents the instant information, and can also be used to summarize the multiple time points or even a full exercise. Multiple designs were proposed, based on an interactive process and two evaluation stages. We concluded that both designs performed similarly.

We discussed the challenges of comparing the multi-dimensional time-varying data provided by the sensors and evaluate the potential of ComVis-Sail with a group of sailing experts. Besides an initial evaluation and demonstration with two coaches, we joined three practice sessions with coaches and sailors, and we analyse their data with different scenarios.

In general, the coaches see the potential of ComVis-Sail to be used on their analysis. As shown during the evaluation sessions, the dashboard helps them to analyse hypothesis on the difference of performance. It also aids in getting more detailed information specially how the boats combine the variables and how they evolve.

As future work, it is interesting to scale the application up for comparing multiple exercises. It would allow to analyse the winning combination of variables during the whole session. Communication and educative requirements should be added in order to enable the coach to share better information extracted from the dashboard. In addition, we plan to work on the missing features mentioned by the coaches during the evaluation.

Despite the specificity of the *Line-up*, the tasks and data that are formulated are in many aspects similar to other racing disciplines where performance is often explained by comparisons. For example, in car racing, to figure out which car is performing better, a car racing manager will compare specific segments or entire laps of a circuit between its car and a reference car. In this case, the spatial alignment between the car trajectories is crucial and the circuits have well-defined spatial references. For two aligned cars, a good measure of performance would be the evolution of their distance to each other (**T1**). After identifying interesting segments, one would study why there are differences. This analysis can start by comparing the distribution of the variables (**T2a**) between the cars, then followed by comparison of the relation between the variables (**T2b**) such as acceleration, breaking and steering. To obtain more details, they can compare the temporal evolution of the variables (**T3**).

## References

- [AAA\*21] ANDRIENKO G., ANDRIENKO N., ANZER G., BAUER P., BUDZIAK G., FUCHS G., HECKER D., WEBER H., WROBEL S.: Constructing spaces and times for tactical analysis in football. *IEEE Transactions on Visualization and Computer Graphics* 27, 4 (2021), 2280–2297.
- [AAB\*17] ANDRIENKO G., ANDRIENKO N., BUDZIAK G., DYKES J., FUCHS G., LANDESBERGER T. V., WEBER H.: Visual analysis of pressure in football. *Data Mining and Knowledge Discovery* 31, 6 (2017), 1793–1839.
- [AMM\*07] AIGNER W., MIKSCH S., MÜLLER W., SCHUMANN H., TOMINSKI C.: Visualizing time-oriented data – a systematic view. *Computers and Graphics* 31 (June 2007), 401–409.
- [BBDG13] BÖHM C., BREHM R. W., DUGGEN L., GRAF K.: A measurement system for performance monitoring on small sailing dinghies. In *Proceedings of the 21st Chesapeake Sailing Yacht Symposium* (2013).
- [BBW16] BECK F., BURCH M., WEISKOPF D.: A matrix-based visual comparison of time series sports data. In *VMV'16: Proceedings of the Conference on Vision, Modeling and Visualization* (Goslar, DEU, 2016), Eurographics Association, pp. 53–60.
- [BKC\*13] BORGIO R., KEHRER J., CHUNG D. H. S., MAGUIRE E., LARAMEE R. S., HAUSER H., WARD M., CHEN M.: Glyph-based Visualization: Foundations, Design Guidelines, Techniques and Applications. In *Proceedings of the Eurographics 2013 - State of the Art Reports* (2013), M. Sbert and L. Szirmay-Kalos (Eds.), The Eurographics Association. <https://doi.org/10.2312/conf/EG2013/stars/039-063>
- [CAFG12] CORRELL M., ALBERS D., FRANCONERI S., GLEICHER M.: Comparing averages in time series data. In *CHI'12: Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (New York, NY, USA, 2012), Association for Computing Machinery, pp. 1095–1104. <https://doi.org/10.1145/2207676.2208556>
- [CLP\*13] CHUNG D., LEGG P., PARRY M., BOWN R., GRIFFITHS I., LARAMEE R., CHEN M.: Glyph sorting: Interactive visualization for multi-dimensional data. *Information Visualization* 14 (Apr. 2013). <http://doi.org/10.1177/1473871613511959>
- [CSB\*20] ÇAKMAK E., SCHÄFER H., BUCHMÜLLER J., FUCHS J., SCHRECK T., JORDAN A., KEIM D.: Motionglyphs: Visual abstraction of spatio-temporal networks in collective animal behavior. *Computer Graphics Forum* 39, 3 (2020), 63–75.
- [DKVS14] DIETRICH C. A., KOOP D., VO H. T., SILVA C. T.: Baseball4d: A tool for baseball game reconstruction and visualization. In *Proceedings of the 2014 IEEE Conference on Visual Analytics Science and Technology (VAST)* (2014), 23–32.
- [DTW\*15] DUFFY B., THIYAGALINGAM J., WALTON S., SMITH D., TREFETHEN A., KIRKMAN-BROWN J., GAFFNEY E., CHEN M.: Glyph-based video visualization for semen analysis. *IEEE*

- Transactions on Visualization and Computer Graphics* 21 (2015), 980–993.
- [DY20] DU M., YUAN X.: A survey of competitive sports data visualization and visual analysis. *Journal of Visualization* 24 (Aug. 2020). <http://doi.org/10.1007/s12650-020-00687-2>
- [ED07] ELLIS G., DIX A.: A taxonomy of clutter reduction for information visualisation. *IEEE Transactions on Visualization and Computer Graphics* 13, 6 (2007), 1216–1223.
- [GKW13] GRINSTEIN G., KEIM D., WARD M.: What's the score?—the 1st workshop on sports data visualization. In *Proceedings of the IEEE Visualization Workshop #1 Notes* (Oct. 2013). <http://workshop.sportvis.com/agenda.html>
- [Gle18] GLEICHER M.: Considerations for visualizing comparison. *IEEE Transactions on Visualization and Computer Graphics* 24, 1 (2018), 413–423.
- [Gol12] GOLDSBERRY K.: CourtVision: New visual and spatial analytics for the NBA. In *Proceedings of the P2012 MIT Sloan Sports Analytics Conference* (2012).
- [HW13] HEINRICH J., WEISKOPF D.: State of the Art of Parallel Coordinates. In *Proceedings of the Eurographics 2013 - State of the Art Reports* (2013), M. Sbert and L. Szirmay-Kalos (Eds.), The Eurographics Association. <http://doi.org/10.2312/conf/EG2013/stars/095-116>
- [ID90] INSELBERG A., DIMSDALE B.: Parallel coordinates: A tool for visualizing multi-dimensional geometry. In *Visualization '90: Proceedings of the First IEEE Conference on Visualization* (1990), pp. 361–378. <http://doi.org/10.1109/VISUAL.1990.146402>
- [JME10a] JAVED W., McDONNELL B., ELMQVIST N.: Graphical perception of multiple time series. *IEEE Transactions on Visualization and Computer Graphics* 16, 6 (2010), 927–934.
- [JME10b] JAVED W., McDONNELL B., ELMQVIST N.: Graphical perception of multiple time series. *IEEE Transactions on Visualization and Computer Graphics* 16, 6 (2010), 927–934.
- [LB15] LOT R., BIANCO N.: Lap time optimisation of a racing go-kart. *Vehicle System Dynamics* 54 (Dec. 2015), 1–21.
- [LCP\*12] LEGG P., CHUNG D. H. S., PARRY M. L., JONES M. W., LONG R., GRIFFITHS I. W., CHEN M.: Matchpad: Interactive glyph-based visualization for real-time sports performance analysis. *Computer Graphics Forum* 31, 3 (2012), 1255–1264.
- [LLW\*20] LI Q., LIN H., WEI X., HUANG Y., FAN L., DU J., MA X., CHEN T.: *MaraVis: Representation and Coordinated Intervention of Medical Encounters in Urban Marathon*. Association for Computing Machinery, New York, NY, USA, 2020, pp. 1–12. <https://doi.org/10.1145/3313831.3376281>
- [LMK07] LAM H., MUNZNER T., KINCAID R.: Overview use in multiple visual information resolution interfaces. *IEEE Transactions on Visualization and Computer Graphics* 13, 6 (2007), 1278–1285.
- [MF18] MEYER M., FISHER D.: *Making Data Visual: A Practical Guide to Using Visualization for Insight*. O'Reilly Media, Incorporated, Sebastopol, CA, 2018.
- [MRS\*12] MAGUIRE E., ROCCA-SERRA P., SANSONE S., DAVIES J., CHEN M.: Taxonomy-based glyph design—with a case study on visualizing workflows of biological experiments. *IEEE Transactions on Visualization and Computer Graphics* 18, 12 (2012), 2603–2612.
- [Mun09] MUNZNER T.: A nested model for visualization design and validation. *IEEE Transactions on Visualization and Computer Graphics* 15, 6 (2009), 921–928.
- [NTMM14] NYLANDER S., THOLANDER J., MUELLER F., MARSHALL J.: HCI and sports. In *CHI EA'14: Proceedings of the CHI '14 Extended Abstracts on Human Factors in Computing Systems* (New York, NY, USA, 2014), Association for Computing Machinery, pp. 115–118. <https://doi.org/10.1145/2559206.2559223>
- [OCT\*13] OLIVEIRA G., COMBA J., TORCHELSEN R., PADILHA M., SILVA C.: Visualizing running races through the multivariate time-series of multiple runners. In *Proceedings of the 2013 XXVI Conference on Graphics, Patterns and Images* (2013), pp. 99–106.
- [Pai20] PAINE N.: Why Michael Jordan was the best. <http://shorturl.at/pzG13> (2020). Accessed: 2020-04-21.
- [PJHY20] POLK T., JÄCKLE D., HÄUBLER J., YANG J.: Courttime: Generating actionable insights into tennis matches using visual analytics. *IEEE Transactions on Visualization and Computer Graphics* 26, 1 (2020), 397–406.
- [PVS\*18] PERIN C., VUILLEMOT R., STOLPER C. D., STASKO J. T., WOOD J., CARPENDALE S.: State of the art of sports data visualization. *Computer Graphics Forum* 37 (2018). <https://doi.org/10.1111/cgf.13447>
- [PYHZ14] POLK T., YANG J., HU Y., ZHAO Y.: Tennis: Visualization for tennis match analysis. *IEEE Transactions on Visualization and Computer Graphics* 20 (Dec. 2014), 2339–2348.
- [QR] QUELAY K., ROBERTS G.: All the medalists: Men's 100-meter sprint. <http://shorturl.at/yBSTY> (2012). Accessed: 2020-04-21.
- [SMM12] SEDLMAIR M., MEYER M., MUNZNER T.: Design study methodology: Reflections from the trenches and the stacks. *IEEE Transactions on Visualization and Computer Graphics* 18, 12 (2012), 2431–2440.
- [Ste81] STEVENS K. A.: The visual interpretation of surface contours. *Artificial Intelligence* 17, 1 (1981), 47–73.
- [SvdWvW14] SCHEEPENS R., v D WETERING H., v WIJK J. J.: Non-overlapping aggregated multivariate glyphs for moving objects. In *Proceedings of the 2014 IEEE Pacific Visualization*

- Symposium* (2014), pp. 17–24. <http://doi.org/10.1109/PacificVis.2014.13>
- [TV218] TV2: Tv 2 Denmark tour de France 2018 studio. <http://shorturl.at/ivHU5> (2018). Accessed: 2020-04-21.
- [War02] WARD M.: A taxonomy of glyph placement strategies for multidimensional data visualization. *Information Visualization 1* (Dec. 2002), 194–210.
- [War08] WARD M. O.: *Multivariate Data Glyphs: Principles and Practice*. Springer, Berlin, Heidelberg, 2008, pp. 179–198. [http://doi.org/10.1007/978-3-540-33037-0\\_8](http://doi.org/10.1007/978-3-540-33037-0_8)
- [WLS\*17] WU Y., LAN J., SHU X., Ji C., ZHAO K., WANG J., ZHANG H.: iTTVis: Interactive visualization of table tennis data. *IEEE Transactions on Visualization and Computer Graphics* (Aug. 2017), vol 24. <http://doi.org/10.1109/TVCG.2017.2744218>
- [WXW\*19] WU Y., XIE X., WANG J., DENG D., LIANG H., ZHANG H., CHENG S., CHEN W.: Forvizor: Visualizing spatio-temporal team formations in soccer. *IEEE Transactions on Visualization and Computer Graphics 25, 1* (2019), 65–75.
- [WZD\*20] WANG J., ZHAO K., DENG D., CAO A., XIE X., ZHOU Z., ZHANG H., WU Y.: Tac-Simur: Tactic-based simulative visual analytics of table tennis. *IEEE Transactions on Visualization and Computer Graphics 26, 1* (2020), 407–417.
- [ZCY\*19] ZHANG M., CHEN L., YUAN X., HUANG R., LIU S., YONG J.: Visualization of technical and tactical characteristics in fencing. *Journal of Visualization 22* (2019), 109–124.

### Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Data S1

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