

Evaluating the Parallel Coordinates Explorable Explainer (PCEE)

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Evaluating the Parallel Coordinates Explorable Explainer (PCEE)

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Abstract

Multidimensional data arises throughout modern science, engineering, and business. Information visualisation offers several techniques to help users explore and analyse multidimensional data. The parallel coordinates technique draws each dimension as its own vertical axis and each record as a polyline. A single plot therefore scales to many dimensions and grows only linearly in complexity. This expressive power is hard for newcomers to grasp. They must learn to read polylines, to order axes usefully, and to apply interaction techniques such as brushing and filtering.

Explorable explainers are interactive tutorials which aim to lower this learning barrier. They interleave explanatory text with interactive illustrations. Readers can experiment with a live visualisation as they read. The Parallel Coordinates Explorable Explainer (PCEE) applies this approach to parallel coordinates. PCEE is an open-source, interactive web application. It uses scrollytelling to keep the narrative and the embedded charts in sync.

This thesis first situates PCEE within the relevant theory. It covers multidimensional data visualisation and explorable explainers. It then covers usability evaluation, looking at inspection methods such as heuristic evaluation and user-based methods such as thinking aloud testing. The thesis then describes a thinking aloud test conducted for PCEE. Five representative test users each worked through the PCEE tutorial and performed five focused follow-up tasks. They verbalised their thoughts throughout. The recorded sessions were distilled into positive and negative findings. Members of the project team then rated and ranked these findings by positivity and severity. The thinking aloud test produced three positive findings and eleven usability problems.

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Credits

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- The thesis was written using Keith Andrews' skeleton thesis [Andrews 2021].

Chapter 1

Introduction

Multidimensional data is used in modern science, engineering, and business. As the number of dimensions grows, traditional two-dimensional plots become insufficient for conveying the relationships hidden within the data. A rich landscape of visualisation techniques has emerged to address this. Among them, parallel coordinates occupy a particularly prominent role: every dimension is drawn as its own axis, so a single plot can accommodate many dimensions at once [Inselberg 2009, pages 3–4]. This comes at a price. The technique is unfamiliar to most newcomers, who first have to learn how to read polylines, why the ordering of axes matters, and how interaction techniques such as brushing and filtering work before the plots become meaningful to them.

Teaching an unfamiliar visualisation technique from static text and images alone is difficult. Explorable explainers offer an alternative [Victor 2011a]: they interleave explanatory text with interactive illustrations, letting readers manipulate a visualisation as they read and build intuition through direct experimentation. The Parallel Coordinates Explorable explainer (PCEE) applies this idea to parallel coordinates [Andrews and Gruber 2025; Andrews and Gruber 2026a]. It is an open-source, interactive web application which guides readers from the basic representation through to advanced interaction techniques, and is designed to be used for independent study and as teaching material in a university course.

A tool intended for learning is only useful, if it is itself usable. To obtain formative feedback on PCEE, two complementary usability evaluation methods were applied. In a heuristic evaluation, several experts inspected the interface independently and judge it against a small set of established usability principles, called heuristics, in order to predict where problems are likely to occur. In a thinking aloud test, representative test users carried out realistic tasks with the application, while continuously verbalising their thoughts, so that observers can see where and why they run into difficulties. Together, the two methods provided both expert-driven and user-driven perspectives on the strengths and weaknesses of PCEE. The heuristic evaluation is reported separately [Zollner 2025a; Zollner 2025b]. This thesis presents the thinking aloud test, whose goal was to uncover concrete usability problems and positive aspects of PCEE from the perspective of representative test users, and so to provide formative feedback for improving the application.

The thinking aloud test produced three positive findings and eleven usability problems. Users appreciated that hovering over a polyline reveals its value on every axis. They also liked that the mouse cursor signals the available actions. Several problems were more serious. Entering the value zero into the data table prevented the chart from being redrawn. Dense charts offered no way to zoom in and trace an individual polyline. The chart context menus were hard to discover. Selecting a thin polyline was error-prone. The instructions for the interactive case study were hard to understand. Despite these problems, participants understood the parallel coordinates technique after using PCEE. They also found working through the tutorial a pleasant experience. The findings give concrete, prioritised guidance for

improving the application. More generally, they show how a formative evaluation based on thinking aloud can inform the design of an educational visualisation tool.

The thesis is organised in two parts. The first part sets the context. Chapter 2 reviews the main techniques for visualising multidimensional data addressing scatterplots, similarity maps, and parallel coordinates. The concept of explorable explainers, together with PCEE and its underlying Steerable Parallel Coordinates in D3 (SPCD3) library [Andrews and Gruber 2026f], is described in Chapter 3. Chapter 4 describes the two main methods of usability evaluation: heuristic evaluation (a usability inspection method) and thinking aloud testing (a usability testing method). The second part presents the original work. Chapter 5 sets out the test plan for the thinking aloud study. Chapter 6 describes the study itself and the results. Finally, Chapter 7 compares the findings of the thinking aloud test with those of the heuristic evaluation. The materials used by the project team and the questionnaires completed by the test users are reproduced in Appendices A and B.

Chapter 2

Multidimensional Data Visualisation

Data with more than two or three dimensions is referred to as *multidimensional* (or *multivariate*) data. Such data arises naturally in almost every scientific and engineering discipline. A chemical process, for example, can be monitored by hundreds of sensors, and a genomic study may measure thousands of gene expression levels simultaneously. Multidimensional data is typically stored in a table or spreadsheet. By convention, *dimensions* (or *variables*) are represented by columns, whereas *records* (or *data items*, or *data points*) are represented by rows. Dimensions are typically either *numerical* (numbers) or *categorical* (strings). An *outlier* is a record whose data points differ significantly from other records in one or more dimensions. A *cluster* is a group of records which have similar characteristics. The Student Marks dataset [Drescher et al. 2023, page 2] is used as a running example throughout this thesis. It contains the fictitious marks of 30 students across eight school subjects, and is shown in Table 2.1.

Visualising multidimensional data is hard and the human visual perception is limited to three spatial dimensions. At the same time, vision is our richest source of information about the world. The brain assigns around 20 billion neurons to processing what we see, a system which is remarkably good at picking out patterns [Ware 2021, page 2]. A variety of visualisation techniques have been developed to exploit the characteristics of the human visual perception system to make high-dimensional datasets more readily interpretable. This chapter describes three widely used techniques for multidimensional data visualisation: scatterplots, similarity maps, and parallel coordinates. At the end of the chapter, a short overview of tools for multidimensional visual analysis is provided.

2.1 Scatterplots

A scatterplot displays the relationship between two quantitative dimensions by plotting each record as a point in a two-dimensional plane. One dimension is mapped to the horizontal axis, and the other to the vertical axis. This form of visualisation works well, because of the human ability to perceive relative position accurately [Ward et al. 2015, page 286]. Friendly and Denis [2005, page 103] state that the scatterplot can be considered the most versatile and generally useful invention in the history of statistical graphics. They characterise it as a plot of two dimensions measured independently on the same observations and drawn as individual points against a pair of (orthogonal) axes. There is no strict functional relationship assumed between them, so that the form of the association between the two variables becomes visible. Figure 2.1 shows a scatterplot of the Maths and English dimensions of the Student Marks dataset, revealing a roughly inverse relationship between the two subjects.

Name	Maths	English	PE	Art	History	IT	Biology	German
Adrian	95	24	82	49	58	85	21	24
Amelia	92	98	60	45	82	85	78	92
Brooke	27	35	84	45	23	50	15	22
Chloe	78	9	83	66	80	63	29	12
Dylan	92	47	91	56	47	81	60	51
Emily	67	3	98	77	25	100	50	34
Evan	53	60	97	74	21	78	72	75
Finn	42	73	65	52	43	61	82	85
Gia	50	81	85	80	43	46	73	91
Grace	24	95	98	94	89	25	91	69
Harper	69	9	97	77	56	94	38	2
Hayden	2	72	74	53	40	40	66	64
Isabella	8	99	84	69	86	20	86	85
Jesse	63	39	93	84	30	71	86	19
Jordan	11	80	87	68	88	20	96	81
Kai	27	65	62	92	81	28	94	84
Kaitlyn	7	70	51	77	79	29	96	73
Lydia	75	49	98	55	68	67	91	87
Mark	51	70	87	40	97	94	60	95
Monica	62	89	98	90	85	66	84	99
Nicole	70	8	84	64	26	70	12	8
Oswin	96	14	62	35	56	98	5	12
Peter	98	10	71	41	55	66	38	29
Renette	96	39	82	43	26	92	20	2
Robert	78	32	98	55	56	81	46	29
Sasha	87	1	84	70	56	88	49	2
Sylvia	86	12	97	4	19	80	36	8
Thomas	76	47	99	34	48	92	30	38
Victor	5	60	70	65	97	19	63	83
Zack	19	84	83	42	93	15	98	95

Table 2.1: The fictitious Student Marks dataset [Drescher et al. 2023, page 2], used as an example throughout this thesis.

2.1.1 The Influence of Scaling

Even for a simple scatterplot of two dimensions, the choice of axis scaling can dramatically change how the data is perceived. Ward et al. [2015, pages 3–4] illustrate this with four scatterplots of the same dataset (city fuel economy versus retail price of cars), each using a different axis scaling. The same effect is reproduced in Figure 2.2 using the Maths vs. English pair from the Student Marks dataset. When both axes use a uniformly large scale, the data collapses into a tight cluster and no structure is visible. Stretching only the y -axis produces what appears to be a horizontal linear pattern. Stretching only the x -axis instead suggests a vertical pattern. When the axes are scaled to the actual range of the data, the inverse proportionality of the data is apparent. This example shows that even with a technique as straightforward as the scatterplot, design choices such as scaling can distort or reveal the structure of the data.

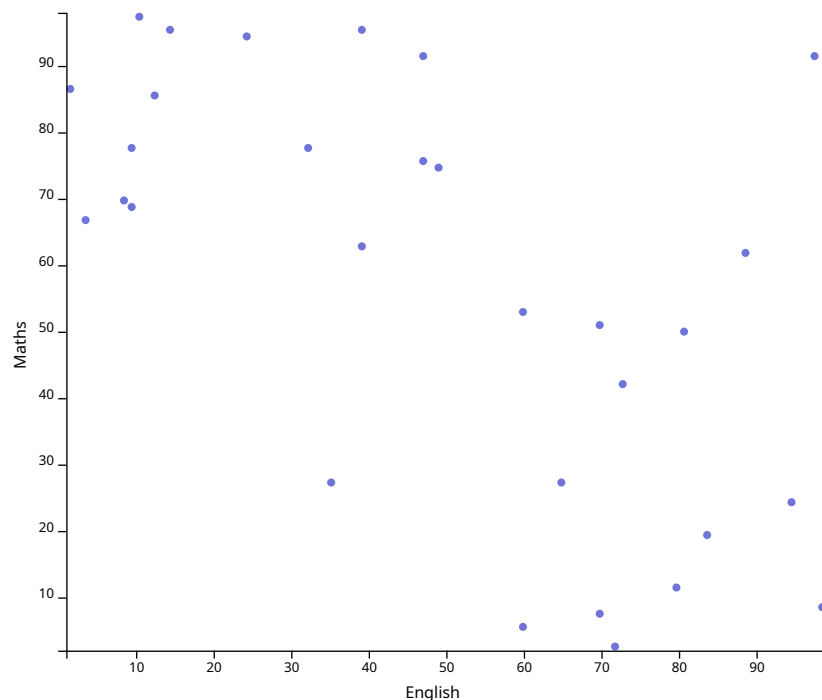


Figure 2.1: Scatterplot: The Student Marks dataset, showing marks in Maths versus English for 30 students.
[Graphic created by the author in Python using matplotlib.]

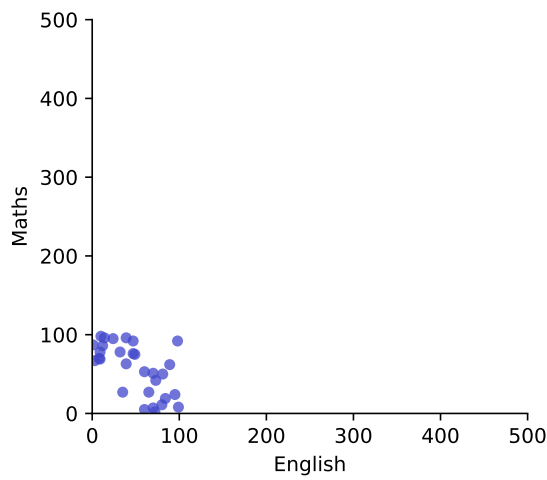
2.1.2 Showing More Than Two Dimensions

Since a scatterplot can only show the relationship between two dimensions at a time, several strategies have been developed to handle higher-dimensional data. Ward et al. [2015, page 286] identify four main approaches:

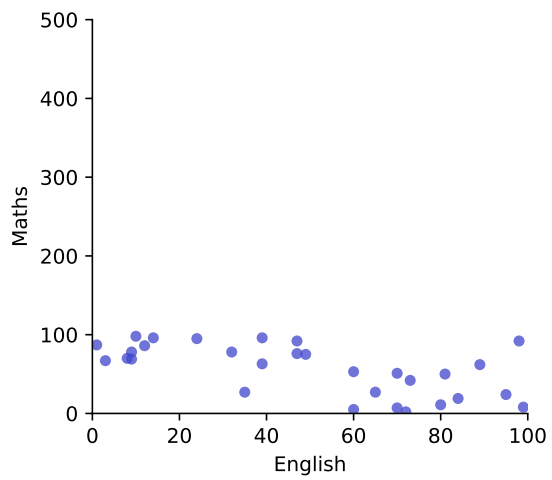
- *Dimension Subsetting*: Selecting a subset of dimensions to display.
- *Dimension Reduction*: Using techniques such as Principal Component Analysis or Multidimensional Scaling to project the data to fewer dimensions.
- *Dimension Embedding*: Mapping additional dimensions to visual properties such as colour, size, or shape.
- *Small Multiples*: Showing several plots side by side or superimposed, each covering some of the dimensions.

One form of dimension embedding is *size mapping*, where the radius or area of each point is scaled by a third numeric dimension. Size expresses gradual increments over a range, which makes it a natural fit for interval and continuous dimensions, whereas categorical dimensions can only be encoded when the number of categories is small, since similarly sized marks become hard to tell apart [Ward et al. 2015, page 151]. Where the third dimension is mapped to circle area, point size remains a comparatively coarse channel. Ware [2021, pages 171–172] groups area with angle, hue, saturation, and texture density in the class of encodings which are generally judged less accurately than position and length. What point size gains in return is range, since area can cover far larger ratios than length within the same amount of screen space. Even so, colour and point size together are a well established way of pushing a scatterplot to three or four dimensions [Ware 2021, page 220]. Figure 2.3 reuses the Maths vs. English layout from Figure 2.1 and adds History as a third dimension, encoded as circle area.

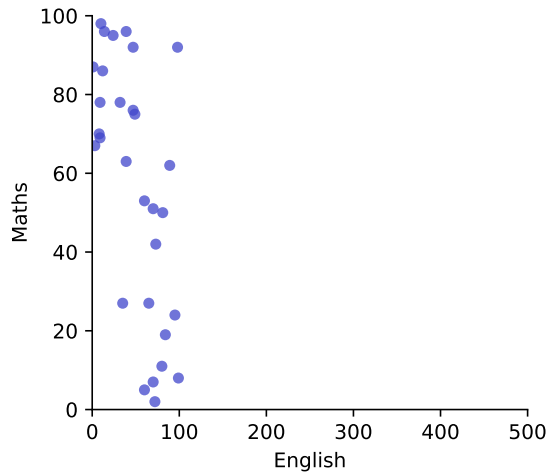
The most common form of small multiples is the *scatterplot matrix* (SPLOM), a grid of $N \times N$ cells



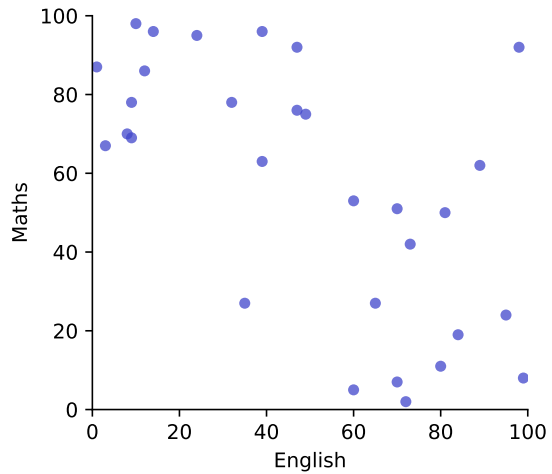
(a) Both axes wide.



(b) Wide y-axis.



(c) Wide x-axis.



(d) Both axes scaled to data range.

Figure 2.2: Scatterplot: The Maths vs. English scatterplot of the Student Marks dataset, shown under four different axis scalings. The roughly inverse relationship between the two dimensions is only apparent when both axes are scaled to the data range. [Graphic created by the author in Python using matplotlib.]

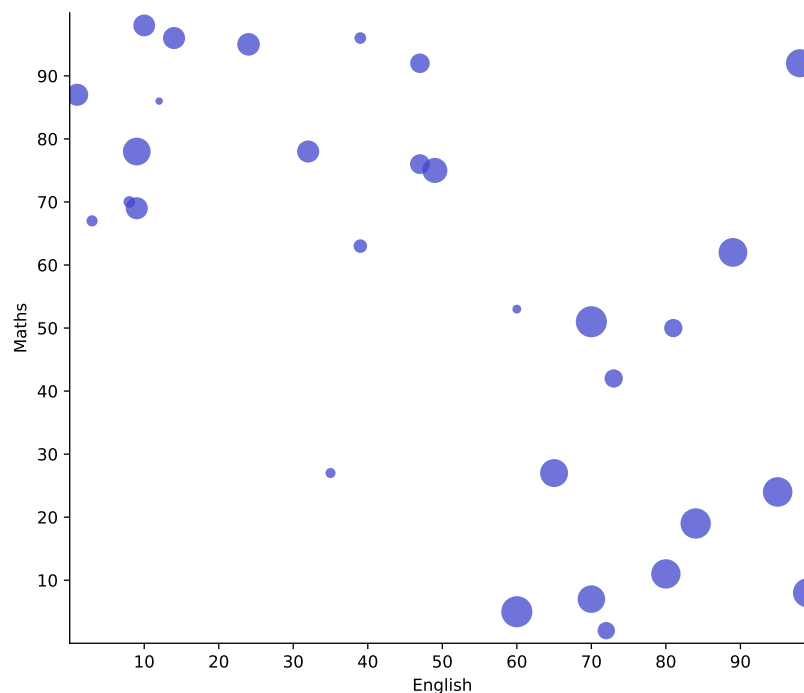


Figure 2.3: Scatterplot: Size coding used in the Student Marks dataset to map the History dimension to circle area. [Graphic created by the author in Python using matplotlib.]

holding one scatterplot for every pair drawn from N dimensions. Rows and columns follow the same sequence of dimensions, so each pair is reachable from either direction and occupies two cells whose axes are interchanged, one the 90° rotation of the other. Along the diagonal, row and column meet on one and the same dimension, so a plot there would be meaningless and the cell is given over to the dimension name or to a histogram of its distribution [Ward et al. 2015, page 286]. A SPLOM makes every pairwise relationship visible at once. However, structure which only becomes visible once three or more dimensions act together escapes it [Ware 2021, page 221].

2.2 Similarity Maps

Similarity maps place a collection of items in a 2d layout, where proximity indicates the similarity between items. These items are typically points in an n -dimensional space, and their coordinates are projected into a 2d space using *dimension reduction methods* (also called *projection methods*) [Christman et al. 2021; Wang et al. 2021]. Instead of plotting a pair of dimensions, they project the entire high-dimensional dataset to a low-dimensional (typically 2d) space, while attempting to preserve the relative distances between records. Records which resemble one another are drawn close together, and the further apart two records are placed, the less they have in common. Some dimension reduction methods are based on a similarity metric between records, others use a dissimilarity metric. Figure 2.4 shows a similarity map of the Student Marks dataset, where all eight subject dimensions are projected onto the plane using Principal Component Analysis (PCA, see Section 2.2.1). Students with comparable overall mark profiles appear close to one another, while students with unique profiles appear as outliers.

Dimension reduction is worthwhile, because the records of a high-dimensional dataset frequently sit on or beside a structure of much lower dimension, a *manifold*, folded through the full data space. Where that is the case, keeping similar records adjacent matters more than reproducing every large distance, and a linear projection cannot generally do so [van der Maaten and Hinton 2008, page 2580].

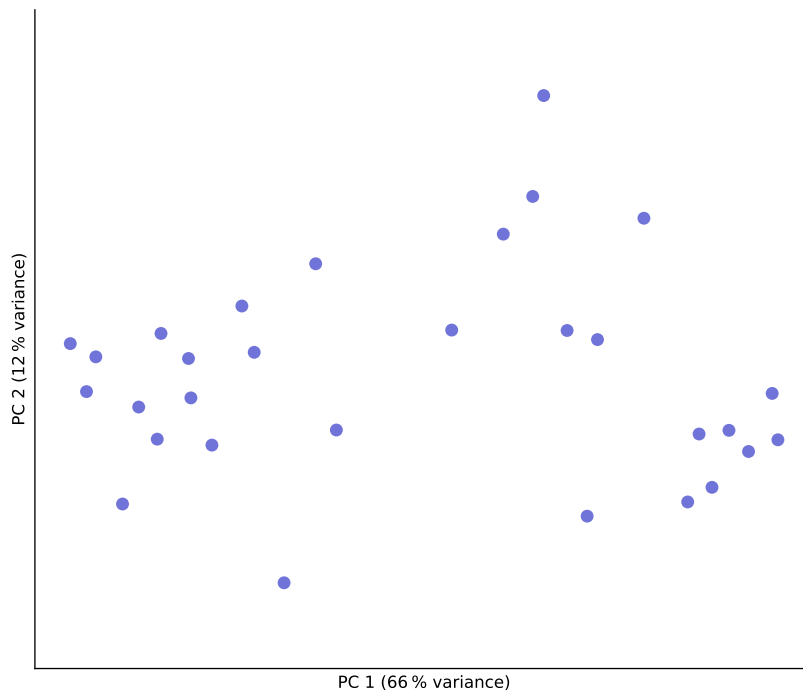


Figure 2.4: Similarity Map: The Student Marks dataset, projecting all eight subject dimensions onto the plane with PCA. The two axes are the first two principal components, together capturing about 78% of the variance. [Graphic created by the author in Python using matplotlib.]

2.2.1 Principal Component Analysis (PCA)

When many dimensions are correlated, much of the variation in a dataset can be captured with fewer axes. Ward et al. [2015, pages 65–67] present *Principal Component Analysis* (PCA) as a classical linear technique that exploits this, reducing the dimensionality of a dataset while preserving as much of its information as possible. PCA constructs new dimensions, the *principal components*, each of which is a weighted sum of the original dimensions. The first component points along the direction of highest variance in the data, the second along the next-highest direction that is orthogonal to the first, and so on. The components are obtained from an *eigendecomposition*, which means that the data is centred on its mean, the covariance matrix is formed, and its *eigenvectors* give the principal components, sorted by *eigenvalue*. In this ordering, each component captures less of the variance than the previous one. Using only the first two or three principal components yields the linear approximation of the data with the smallest average error among all such low-dimensional projections. The similarity map is produced by plotting the data using these components as axes.

Since PCA is a linear projection, it is fast and deterministic and produces stable, reproducible layouts. However, it can only recover structure which is itself linear. If the data sits on a non-linear manifold, a linear projection cannot unfold it, and neighbouring points on the manifold can end up far apart. van der Maaten and Hinton [2008, page 2580] argue that non-linear techniques are typically the better choice in this situation. PCA nevertheless keeps its role in the processing pipeline as a preprocessing step. Before running t-SNE (see Section 2.2.3), they first reduce their data to 30 dimensions with PCA, which speeds up the computation of pairwise distances and suppresses some of the noise [van der Maaten and Hinton 2008, page 2589].

2.2.2 Multidimensional Scaling (MDS)

Another important dimension reduction algorithm is *Multidimensional Scaling* (MDS) [Ward et al. 2015, page 287]. Given an $n \times n$ matrix of pairwise distances (similarities) between records, MDS seeks a configuration of n points in a low-dimensional space that minimises a *stress* function. The stress measures the discrepancy between the original distance matrix and the distance matrix computed from the current low-dimensional positions. The algorithm iteratively shifts each point in a direction which reduces its individual stress, repeating until the stress is sufficiently small or has converged [Ward et al. 2015, pages 67–68, 287–288]. The result is a layout in which the inter-point distances approximate the original dissimilarities as far as possible. Iterative MDS can converge in fewer steps if PCA is used to supply the initial positions [Ward et al. 2015, page 68].

2.2.3 t-Distributed Stochastic Neighbour Embedding (t-SNE)

t-Distributed Stochastic Neighbour Embedding (t-SNE) was introduced by van der Maaten and Hinton [2008, page 2579] as a nonlinear technique, which assigns every record a position in a 2d plane or in a 3d volume. It refines *Stochastic Neighbour Embedding* (SNE) into a form which is easier to optimise. Unlike MDS, which tries to reproduce every pairwise distance, t-SNE concentrates on local neighbourhoods. Records which lie close together in the high-dimensional space are kept close in the map. The exact placement of distant records is not as important.

The algorithm reaches this map in two stages [van der Maaten and Hinton 2008, pages 2581, 2584–2585]. First, the high-dimensional distances between records are turned into neighbourhood probabilities. A Gaussian distribution centred on each record x_i assigns every other record x_j a probability $p_{j|i}$ of being its neighbour. It is high for nearby records and near zero for distant ones. Second, the records are given positions in the low-dimensional map, where an analogous probability $q_{j|i}$ is computed from those positions. Afterwards the points are shifted until the two distributions match as closely as possible, where the distance is measured by the Kullback-Leibler divergence. One step which sets t-SNE apart from SNE is its use of a heavy-tailed Student t -distribution, rather than a Gaussian distribution for the low-dimensional probabilities. This addresses the *crowding problem*, which states that a high-dimensional neighbourhood holds far more moderately distant records than a flat map has room for at matching distances, and the heavy tails give those records space instead of forcing them together.

Since it preserves local structure in this way, t-SNE shows groupings that linear projections such as PCA tend to blur. On benchmark sets of handwritten digits, faces, and objects, van der Maaten and Hinton [2008, pages 2588–2589, 2592] report that it separates the *natural classes* of the data more effectively than earlier dimension-reduction techniques such as *Isomap* [Tenenbaum et al. 2000] or *Locally Linear Embedding* [Roweis and Saul 2000]. A natural class is the category a record truly belongs to, such as the particular digit a handwritten sample shows. Unlike a cluster, a natural class exists in the data itself, not only in the plot.

The readability of these projections has made t-SNE a popular tool for exploring high-dimensional data, yet the same readability can mislead [Wattenberg et al. 2016]. The resulting map is found by an iterative optimisation from a random start [van der Maaten and Hinton 2008, page 2582]. Runs on the same data usually agree on the global shape, but some datasets yield markedly different diagrams from one run to the next, and the outcome depends strongly on the *perplexity* parameter, which controls how many neighbours each point is weighed against. The size of clusters and distance between them can be misleading. The size of a cluster reflects the local density that t-SNE evens out rather than the number of records it holds, and the gap between two clusters need not correspond to their separation in the original space.

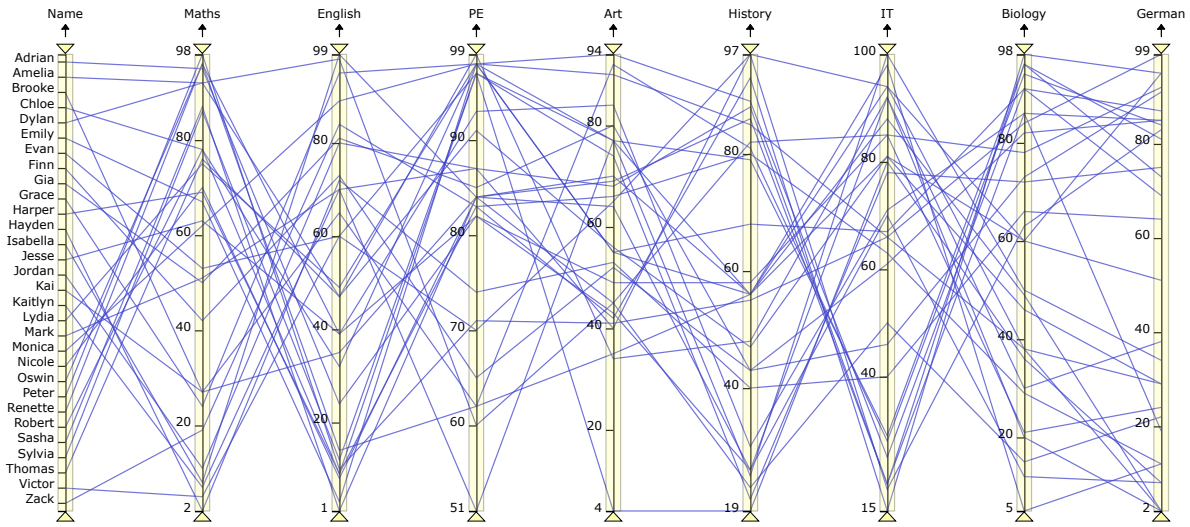


Figure 2.5: Parallel Coordinates: The Student Marks dataset, with one polyline per student crossing the eight subject axes. [Graphic created by the author with SPCD3 [Andrews and Gruber 2026f].]

2.3 Parallel Coordinates

Parallel coordinates offer a fundamentally different approach to visualising multidimensional data. Instead of projecting records into a low-dimensional space, parallel coordinates represent each dimension as a separate parallel vertical axis. A record is drawn as a *polyline*, a line with multiple segments which intersects each axis at the position corresponding to its value for that dimension [Inselberg 2009, page 3]. Figure 2.5 shows a parallel coordinates plot of the Student Marks dataset, with one vertical axis per subject and one polyline per student.

2.3.1 How Parallel Coordinates Work

The history of parallel coordinates extends back to the 19th century. Andrews [2026b, page 91] traces the earliest known use to Henry Gannett in 1883, who visualised ten attributes for each of the then 47 states of the United States, shown in Figure 2.6. Maurice d’Ocagne discussed their theoretical foundations in his book of 1885 [d’Ocagne 1885]. Alfred Inselberg independently re-invented parallel coordinates in 1959 [Inselberg 2009, page 2] and popularised them for the digital age with a comprehensive overview paper in 1985 [Inselberg 1985]. He later published the authoritative book on the subject in 2009 [Inselberg 2009].

The central idea of the technique is described by Heinrich and Weiskopf [2013, pages 97–98]. Axes are placed side by side as equally spaced vertical lines, one for each of the N dimensions of the dataset. In the simplest two-dimensional case, a point $A = (a_1, a_2)$ maps to the straight line segment joining position a_1 on the first axis to position a_2 on the second. For $N > 2$ dimensions, this mapping is applied to every adjacent pair of axes, yielding the $N-1$ line segments whose concatenation forms the characteristic polyline. A record $A = (a_1, a_2, \dots, a_N)$ is therefore drawn as a single polyline that crosses each axis X_i at the height corresponding to a_i . Ward et al. [2015, page 295] note that such a plot can be read as a rotated line graph, with the values of one record linked together across all dimensions.

2.3.2 Representing Data as Polygons

A fundamental property of parallel coordinates is the *point-line duality*, which means that a point in the data space maps to a multi-segment line (polyline) in the parallel coordinates plot and a polyline in the data space maps to the point at which the polyline intersects the dimension axes [Heinrich and Weiskopf

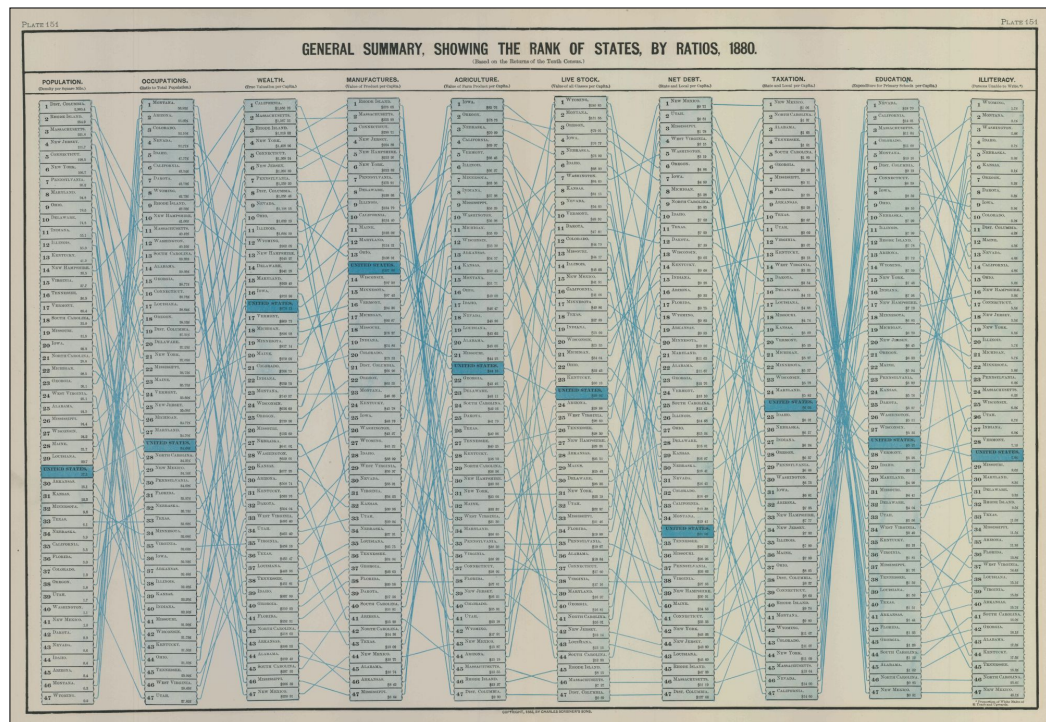


Figure 2.6: Parallel Coordinates: Plate 151 from Hewes and Gannett's Scribner's Statistical Atlas of the United States (1883), ranking the then 47 states of the USA across ten dimensions and connecting each state's ranks by a line [Andrews 2026b, pages 40, 91]. Image courtesy of the Library of Congress, Geography and Map Division.

2013, page 98]. This can be formalised using projective geometry. In the two-dimensional case, a set of records that lie on a common line $\ell: x_2 = m x_1 + b$ produces a family of lines in the plot that all pass through a single *indexed point* $\bar{\ell}$, whose position depends on the slope and intercept of ℓ .

The duality is not limited to points and lines. Heinrich and Weiskopf [2013, page 98] explain that it also extends to curves: a curve in the data space corresponds to the *envelope* formed by its whole family of image lines in the plot, giving a curve-curve duality. Under this correspondence an ellipse turns into a hyperbola, which makes the duality useful when Gaussian distributions are visualised.

Inselberg [2009, pages 115–118] demonstrates the practical power of this representation with an industrial dataset of several thousand records across eight dimensions. When plotted in parallel coordinates, a distinctive vertical-line pattern emerged between two adjacent axes, revealing a previously unknown linear relationship and suggesting that an important dimension had not been measured. A subsequent search confirmed the existence of this missing dimension, illustrating how parallel coordinates can expose hidden structure in high-dimensional data.

2.3.3 Reading Patterns in Parallel Coordinates

A key strength of parallel coordinates is that the complexity of the representation increases only linearly with the number of dimensions, making the technique useful for large datasets. Several characteristic visual patterns can be read directly from the plot [Ward et al. 2015, page 295]:

- *Positive Correlation:* When two adjacent dimensions are positively correlated, the line segments between their axes tend to run in parallel.
- *Negative Correlation:* When two adjacent dimensions are negatively correlated, the line segments cross, forming an X-shaped pattern between the axes.

- *Clusters*: Groups of similar records appear as bundles of lines that follow similar paths.
- *Outliers*: Records with unusual values stand out as lines that deviate from the main bundles, crossing through regions of the plot that are otherwise sparsely populated.

2.3.4 Limitations

Parallel coordinates have some well-known limitations. When the number of records is large, the plot can become cluttered and difficult to read due to *overplotting*: the number of overlapping lines obscures the underlying patterns. Heinrich and Weiskopf [2009, page 1531] proposed *continuous parallel coordinates* as one approach to address this problem, replacing discrete polylines with continuous density representations that more faithfully convey the distribution of the data.

Another fundamental limitation is that the visual appearance of patterns depends on the *ordering of axes*. Correlations and relationships between two dimensions are only perceived when their axes are placed adjacent to one another. Since only $N-1$ of the $\binom{N}{2}$ possible dimension pairings can be adjacent in a single plot, relationships between non-adjacent dimensions are harder to detect [Heinrich and Weiskopf 2013, page 98].

2.3.5 Interaction Techniques

Various interaction techniques have been developed to make parallel coordinates into a powerful tool for interactive data analysis [Heinrich and Weiskopf 2013, pages 104–107; Ward et al. 2015, pages 294–296]:

- *Axis Reordering*: Users can rearrange the order of axes to bring dimensions of interest next to each other, making their pairwise relationships visible.
- *Brushing*: Users can select a range on one or more axes to highlight the corresponding records across all axes. This makes it possible to trace a subset of the data through all dimensions.
- *Filtering*: Users can restrict the displayed data to points which fall within specified ranges on one or more axes, reducing clutter and focusing attention on relevant subsets.
- *Axis Scaling and Flipping*: Individual axes can be rescaled (e.g. logarithmically) or inverted to reveal patterns which are not visible with the default linear scaling.

With these tools, users can iteratively explore and filter the data until patterns emerge.

2.3.6 Parallel Coordinates Matrix

To address the dependence on axis ordering, Heinrich et al. [2012, page 37] propose the *parallel coordinates matrix* (PCM) as the counterpart of the scatterplot matrix for parallel coordinates. Instead of a single plot with a fixed ordering, the PCM is a small set of full-width parallel coordinates plots. Each plot uses a different ordering of the same axes. The orderings are chosen so that every pair of dimensions is adjacent in exactly one of the plots, so all pairwise relations are covered without repeating any pair. For the eight subjects of the Student Marks dataset, four such plots suffice to make every pair of subjects adjacent exactly once, as shown in Figure 2.7.

The authors construct these orderings from a result in graph theory, which guarantees that for a given set of dimensions there is always a small collection of sequences in which every pair of dimensions is adjacent in exactly one sequence. Each sequence becomes one row of the matrix, and each row is a full parallel coordinates plot over all dimensions. Polyline can be traced across all axes within a row, and existing techniques such as brushing, axis reordering, and focus-and-context views carry over to the individual rows without modification.

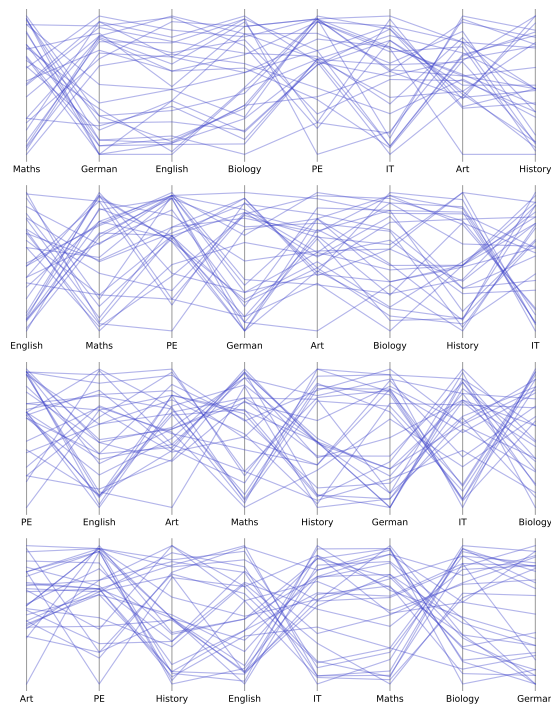


Figure 2.7: Parallel Coordinates Matrix: The Student Marks dataset shown as a parallel coordinates matrix. Each of the four plots draws all eight subject axes in a different order, chosen so that every pair of subjects is adjacent in exactly one plot. [Graphic created by the author in Python using matplotlib.]

Compared with the scatterplot matrix, the PCM uses screen space more economically, because each pair of dimensions is shown once rather than twice [Heinrich et al. 2012, page 39]. The scatterplot matrix in turn gives every pair a fixed row-column address, whereas in the PCM the same pair may appear at different positions in different rows. The authors therefore hypothesise that the scatterplot matrix performs better at finding the relation of a particular pair of dimensions, but note that this has yet to be confirmed by a user study.

2.3.7 Comparison with Scatterplot Matrices

An important question is how well parallel coordinates perform compared with other multidimensional visualisation techniques. Ware [2021, page 224] reports that empirical studies generally suggest that viewers tend to read patterns more easily from a scatterplot matrix than from a parallel coordinates plot. Dimara et al. [2018] compared parallel coordinates, scatterplot matrices, and tabular visualisations on low-level analytic tasks and on a decision-making task. All three techniques reached good accuracy on the analytic tasks, but the scatterplot matrix was best for judging correlations. On the decision-making task the three techniques performed similarly, but parallel coordinates attracted the largest number of negative comments, because they made it hard to compare individual alternatives. Parallel coordinates have a decisive advantage when the number of dimensions is large: a scatterplot matrix with 20 dimensions requires 400 small plots, while a parallel coordinates plot simply adds more axes (one for each dimension).

Date	Tool	Developer	Licence	Platform
1994–2015	XmdvTool	WPI	Source available	Desktop
2013–now	High-D	Macrofocus	Commercial	Desktop
2023–now	MVA	TU Graz	Open source	Browser

Table 2.2: Comparison of the three multidimensional visual analysis tools: XmdvTool, High-D, and MVA.

2.4 Multidimensional Visual Analysis Tools

The techniques described in this chapter are brought together in a number of interactive tools for exploring multidimensional data. Three representative examples are XmdvTool, High-D, and Multidimensional Visual Analyser (MVA):

- *XmdvTool*: XmdvTool [Ward 2015], developed by Matthew Ward and colleagues at Worcester Polytechnic Institute, is a free, source available, cross-platform application and the broadest of the three in the range of techniques. XmdvTool offers scatterplot matrices, parallel coordinates, star glyphs, dimensional stacking, and pixel-oriented displays. Its interaction repertoire includes brushing in screen, data, and structure space, together with zooming, panning, distortion, and dimension reordering.
- *High-D*: High-D [Macrofocus 2026] is a commercial desktop application by Macrofocus, available for Windows, MacOS, and Linux. It concentrates on parallel coordinates, rendering each attribute as a vertical axis and each record as a polyline. In addition to the basic plot, it offers interactive filtering with per-axis sliders, axis reordering and rescaling, density-based rendering to counter overplotting on large datasets, and colour coding to compare groups of records. It is distributed under a paid licence with a 30-day free trial.
- *Multidimensional Visual Analyser (MVA)*: MVA [Golob and Andrews 2024a; Golob and Andrews 2024b], developed at Graz University of Technology, is an open-source tool that runs entirely in the web browser. It encompasses a scatterplot, a scatterplot matrix, a similarity map, and a parallel coordinates plot as multiple coordinated views, so that a selection brushed in one view is highlighted simultaneously in all the others. Figure 2.8 shows the Student Marks dataset in MVA, with a scatterplot matrix, a single scatterplot, a similarity map, and a parallel coordinates plot displayed side by side.

Table 2.2 summarises the three tools. They occupy different points in the design space. XmdvTool provides the widest selection of visualisation techniques, but is a research prototype with an outdated interface. High-D is a polished product specialised for parallel coordinates. MVA is a lightweight, immediately accessible tool, that coordinates scatterplot, similarity-map, and parallel coordinates views.

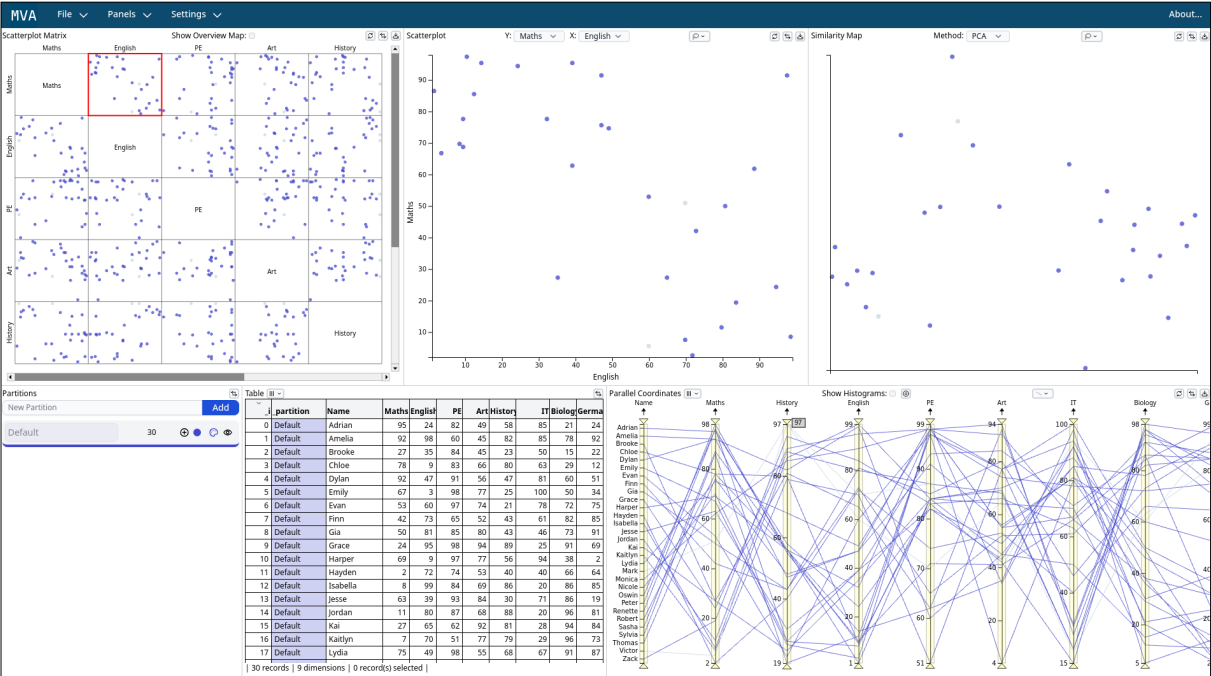


Figure 2.8: MVA: The Student Marks dataset shown with a scatterplot matrix, a single scatterplot, a similarity map, and a parallel coordinates plot side by side.

Chapter 3

Parallel Coordinates Explorable Explainer (PCEE)

Parallel coordinates are a powerful technique for visualising multidimensional data, but they are not easy for newcomers to learn. Teaching such a technique effectively calls for more than static text and images. An interactive tutorial for parallel coordinates might combine textual descriptions with coordinated interactive illustrations.

3.1 Explorable Explainers

Andrews and Gruber [2025] trace the *explorable explainer* back to two roots. The name itself comes from Bret Victor’s 2011 essay Explorable Explanations [Victor 2011a]. The underlying ideas around an *active essay* come from Alan Kay [Kay 1998]. Victor [2011a] notes that books and web sites present only the author’s perspective. Any questions or alternative interpretations remain in the reader’s head, unexpressed and untested. In *active reading*, readers engage critically with text. They challenge assumptions, explore alternatives, and test whether specific examples support general claims. Instead of accepting information passively, they treat the author’s argument as a starting point for their own thinking. An explorable explainer puts text and working code side by side. It leads the reader through a technique step by step. Some charts and illustrations change on their own to make a point. Others are left for the reader to try out. As Victor [2011a] argues, explorable explainers encourage transparency. The author cannot just state a result. The model behind it has to be visible, so readers can check it themselves. A weak model can then be refuted with evidence instead of only doubted. This transparency affects trust. Readers verify claims by playing with parameters and observing results. If an author’s formula is an approximation, readers discover where it holds and where it fails. Self-verification can build a deeper understanding than accepting claims without question.

Victor identifies three main types of interactive elements in an explorable explainer:

- *Reactive Documents*: Readers modify the author’s assumptions and observe how conclusions change. Interaction requires minimal effort, since a click or drag adjusts values instantly.
- *Explorable Examples*: Abstract concepts become tangible. Readers experiment with different parameters and observe the system’s behaviour, developing intuition through direct manipulation.
- *Contextual Information*: Background material appears when needed. Readers can look up unfamiliar terms without leaving the main text.

The explorable elements must integrate with the explanation. The text works as a static explanation. It must be readable without depending on interaction. Readers interact with the explainer when they

want to explore or go deeper. Many interactive tools leave users without guidance, expecting them to discover everything independently. Victor argues this approach fails as explanation. Effective explorable explainers require authorial guidance. The author poses questions, and the reader explores possible answers. Victor’s broader vision is to transform text from passive information delivery into a space where readers actively reason and explore [Victor 2011a].

Today, explorable explainers take many forms, as Andrews and Gruber [2025] note. Some are built as computational notebooks, such as Jupyter notebooks [Jupyter 2026] or Observable notebooks [Observable 2026], whereas others are standalone JavaScript web applications with custom visualisations. A common technique is *scrollytelling*, where the reader’s scroll position drives animations and diagram updates, synchronising the visual with the textual explanation. Notable examples include the Distill journal, which published interactive articles on machine learning topics such as the t-SNE explainer by Wattenberg et al. [2016], and the annual VISxAI workshop [VISxAI 2026], which showcases interactive explanations of AI concepts. Victor’s Tangle library [Victor 2011b] supports reactive documents, where dragging a number in the text updates dependent calculations.

3.2 Steerable Parallel Coordinates in D3 (SPCD3)

Building an explorable explainer for parallel coordinates requires a visualisation component controllable from outside. The explainer must issue commands to the chart at specific times, triggering changes to illustrate concepts. The Steerable Parallel Coordinates in D3 (SPCD3) library was developed for this purpose [Andrews and Gruber 2026f]. The library is written in TypeScript [Microsoft 2026] and delivered as JavaScript [Haverbeke 2024]. Its parallel coordinates chart can be controlled in two ways:

- End users manipulate the visualisation directly through mouse and keyboard.
- External code controls the visualisation programmatically through an application programming interface (API).

SPCD3 is well-suited for explorable explainers, since the application can steer the visualisation while readers remain free to explore it themselves, as can be seen in Figure 3.1. SPCD3 is an open-source project [Andrews and Gruber 2026f]. A live demo is hosted at [Andrews and Gruber 2026e].

3.2.1 Technical Foundation

SPCD3 uses the following modules of D3 (Data-Driven Documents) [Bostock 2026] version 7:

- `d3-dsv`: Parses CSV files.
- `d3-selection`: Selects DOM elements and sets attributes.
- `d3-drag`: Implements drag-and-drop for moving dimensions and adjusting filters.
- `d3-shape`: Draws polylines representing records.
- `d3-axis`: Creates axes for dimensions.
- `d3-scale`: Maps data values to visual positions.
- `d3-transition`: Transforms changes smoothly rather than instantaneously.
- `d3-ease`: Supplies the easing functions which shape those transitions.

SPCD3 uses `d3-interpolate-path`, a third-party module, for interpolating polylines during transitions. It further uses `xml-formatter` to pretty-print exported SVG [Andrews and Gruber 2026f].

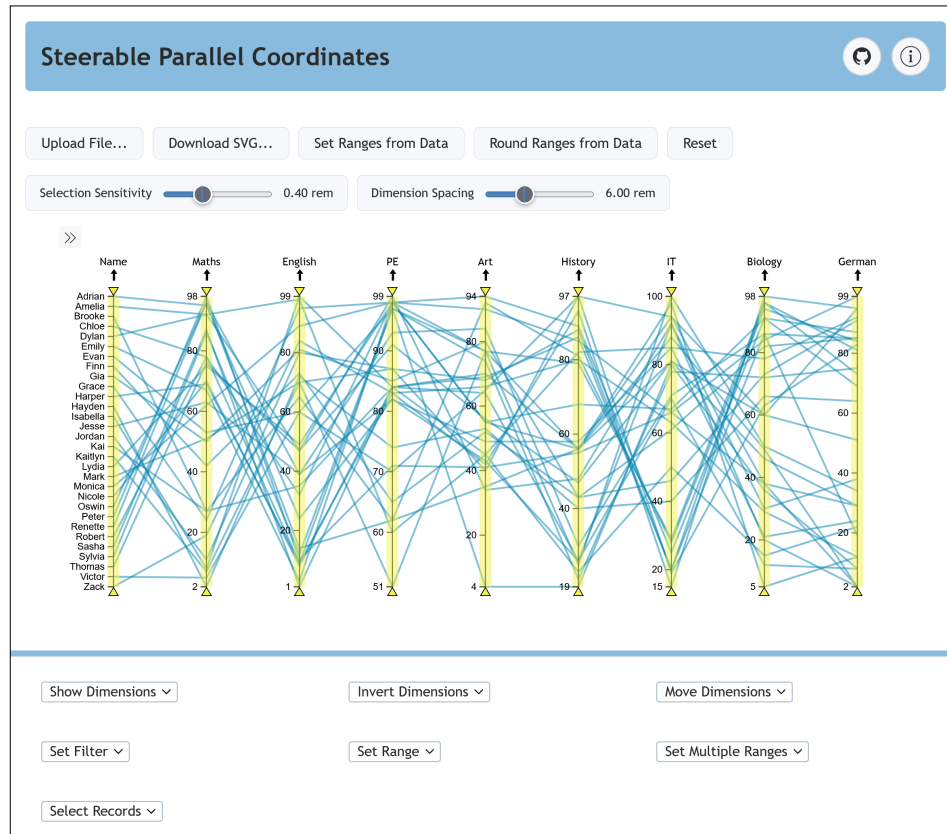


Figure 3.1: SPCD3: The SPCD3 tool showing the Student Marks dataset.

3.2.2 Built-In Interactivity

SPCD3 provides built-in interactive features for the end user to explore multidimensional datasets [Andrews and Gruber 2026d]:

- *Inverting Dimensions:* To invert a dimension, click the arrow button above an axis or use the axis context menu. Inverting helps reveal correlations. Almost parallel polyline segments indicate positive correlation, crossing lines indicate negative correlation.
- *Moving Dimensions:* Drag and drop dimensions to rearrange their order. Correlations are only visible between adjacent dimensions.
- *Hiding Dimensions:* Hide dimensions through the context menu to reduce clutter. Restore with Show All Dimensions. The same menu also copies a dimension name with Copy Name.
- *Adjusting Ranges:* By default, axes show the data's min/max range. The context menu offers Set Range for specific bounds, which helps when the domain is known (e.g. 0 to 100 for percentages). Set Range from Data returns to the original range, and Set Rounded Range from Data to its rounded minimum and maximum.
- *Filtering Records:* Each dimension has a double-edged range slider. Records outside the filter range are inactive and are greyed out. Combine filters across dimensions to isolate records of interest. The context menu sets the same filters numerically with Set Filter and clears them with Reset Filter.
- *Hovering and Selecting:* Hover highlights polylines and shows tooltips. Click to select, shift-click to extend, and control-click to toggle. Selected records appear in a distinct colour.

- *Chart Toolbar*: A toolbar above the chart collects the operations which act on the chart as a whole. Show Table opens the dataset in a table, from which it can also be downloaded as CSV. Download Chart (SVG) exports the chart as SVG. Refresh redraws it, and Reset restores its original state.

3.2.3 Steerable API

In addition, SPCD3 provides an API for autonomous control of the visualisation. The API can be called to trigger specific actions. SPCD3 organises these methods into nine groups [Andrews and Gruber 2026c]:

- *I/O Functions*: Load a dataset from CSV, draw the chart from it, and refresh, reset, or delete it. The chart can also be exported as SVG, either written to a file or returned as a string.
- *Show and Hide Functions*: Hide a dimension, show it again, and query whether it is currently shown or hidden.
- *Invert Functions*: Reverse the direction of a dimension's axis, with or without animation, and read or set its inversion status.
- *Move Functions*: Reorder dimensions by placing one beside another, shifting one a single position, or swapping two, and report the position a dimension currently holds.
- *Range Functions*: Set the range of a dimension to given or rounded values, and read back both the minimum and maximum present in the data and the range currently in effect.
- *Filter Functions*: Set the filter of a dimension numerically and read the values it currently filters on.
- *Selection Functions by Label*: Select and deselect records, toggle them individually, ask whether a record is selected, read back the current selection, and clear it. Records are named by their label, which the library reads from the first column unless told otherwise.
- *Selection Functions by ID*: Repeat the selecting, deselecting, toggling, and querying, but name each record by a numeric identifier rather than by its label. Reading back and clearing the selection is only possible by label.
- *Helper Functions*: Query the current state of the chart, such as its records and dimension names, and adjust presentation details such as record colouring, markers, dimension spacing, and whether interactivity is enabled at all.

3.3 The Parallel Coordinates Explorable Explainer

The Parallel Coordinates Explorable Explainer (PCEE) applies the explorable explainer approach to parallel coordinates in the form of a web application [Andrews and Gruber 2025]. It combines textual explanations with interactive parallel coordinates charts drawn by SPCD3, and is shown in Figure 3.2. PCEE is an open-source project [Andrews and Gruber 2026a]. A live version is hosted at [Andrews and Gruber 2026b].

3.3.1 Motivation

End users are often unfamiliar with parallel coordinates. Using the technique for analysis requires understanding dimension ordering, axis inversion, brushing, and filtering. These concepts can be hard to grasp from static descriptions. An explorable explainer lets readers manipulate the visualisation while reading, combining instruction with hands-on experimentation [Andrews and Gruber 2025].

Interactive tutorials are often used for *onboarding*, to familiarise new users with a user interface or technique. Stoiber et al. [2022, pages 34, 41–42] found that onboarding made little difference for visualisations participants already knew, but did improve how well participants read parallel coordinates, which

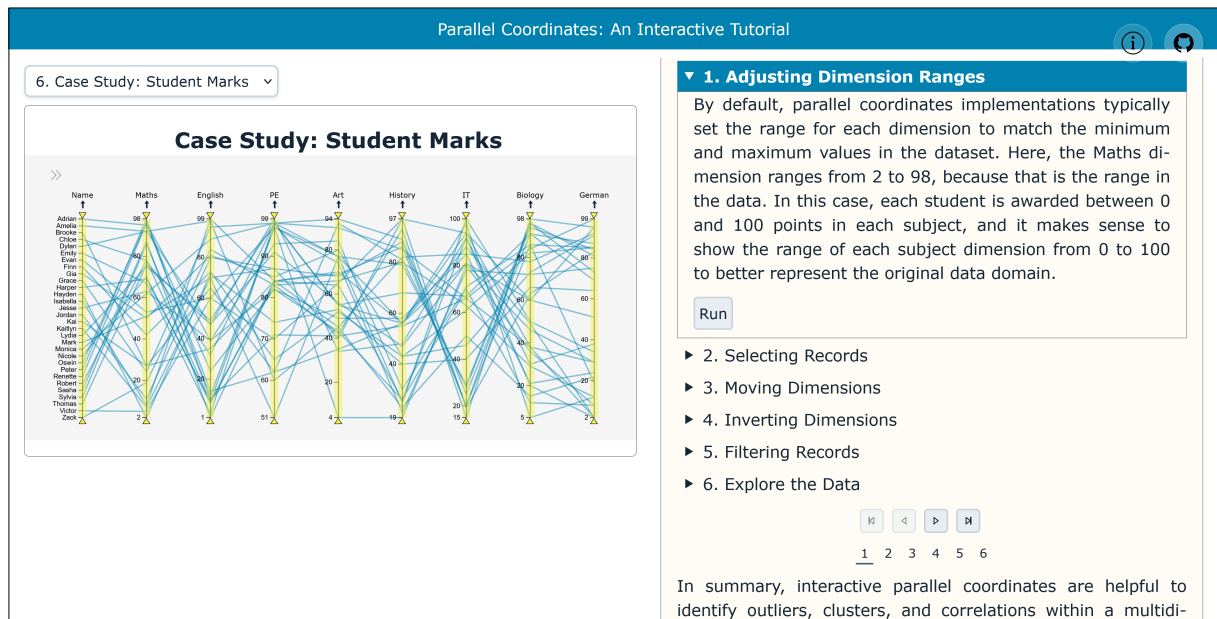


Figure 3.2: PCEE: The Student Marks dataset as part of the PCEE explorable explainer.

was the most unfamiliar visualisation for participants, although the improvement in answer correctness did not reach statistical significance. In a further study, the authors found that participants preferred scrollytelling woven into the tool, rather than instructions offered separately beforehand. PCEE builds on both findings, as it introduces parallel coordinates charts in context, letting explanatory text and the interactive visualisation progress side by side throughout the explainer.

Two user profiles were identified for PCEE:

- *Students in an InfoVis class:* PCEE can be used as an interactive tool during class to demonstrate the concept of parallel coordinates, which can be revisited by students at home.
- *Independent Study:* PCEE can be accessed online, so it is available to a wide audience for independent study.

The goals of both user groups are identical. Users of PCEE want to learn about parallel coordinates by working through an interactive tutorial. The same two user profiles were used for the thinking aloud test (see Section 6.3.2).

3.3.2 Architecture

PCEE is written in TypeScript [Microsoft 2026] and uses Vue.js [Vue 2026]. SPCD3 is used to provide the interactive parallel coordinates charts. PCEE is deployed as a web application, and can be accessed through any modern web browser without installation. In addition, Tauri [Tauri 2026] is used to build native executable packages for Windows, MacOS, and Linux.

3.3.3 Scrollytelling as a Narrative Method

PCEE uses scrollytelling, where scrolling through the text triggers animations and updates to the embedded visualisations. This way, the explanation and the visualisation stay synchronised [Andrews and Gruber 2025]. Three trigger types connect the narrative with the visualisation:

- *Scroll-driven triggers:* Specific changes in scrolling positions automatically trigger visualisation changes. For example, scrolling past a paragraph about filtering might automatically apply a filter.

- *Button triggers*: The reader clicks a button in the narrative text to trigger a corresponding action. For example, a button labelled Move Fitness Score next to Age calls the SPCD3 API to reposition dimensions.
- *Stepper triggers*: The reader steps through a predefined sequence of actions, observing each transformation before proceeding.

Scroll-driven triggers work for simple concepts. Button and stepper triggers are activated manually by the reader and work better when the reader needs to observe each step carefully.

3.3.4 Content and Structure

PCEE guides readers through the parallel coordinates technique, from basic representation to advanced interactions. The content covers:

- How parallel coordinates represent multidimensional data.
- How to read patterns such as clusters, outliers, and correlations.
- How to use interactive features such as dimension reordering, axis inversion, and filtering.
- Practical applications in data analysis.

Chapter 4

Usability Evaluation

Usability can be evaluated in two fundamentally different ways: *usability inspection methods*, in which expert evaluators judge an interface against a set of principles or guidelines, and *usability testing methods*, in which representative real users are observed as they work. Both inspection and testing methods can serve either *formative* or *summative* purposes [Hornbæk et al. 2025, page 710]. Formative evaluation aims to improve a system during development. It identifies problems and informs design decisions. Summative evaluation determines whether a system meets its objectives, typically at the end of a development cycle. Andrews [2026a, Chapter 3] gives an overview of the different usability evaluation methods.

4.1 Usability Inspection Methods

Inspection methods appeared in the late 1980s as a cheaper, faster alternative to laboratory-based usability testing [Lewis and Sauro 2021, page 977]. Instead of observing users, expert evaluators walk through an interface and check it against principles, guidelines, or cognitive models. Wilson [2014, pages ix–x] traces these methods back to software engineering inspections, which Fagan described in 1976 and which usability practitioners took over in the late 1980s. In 1994, Nielsen and Mack [1994] summed up the state of the field. Hornbæk et al. [2025, page 719] use the term *analytical evaluation methods* for this category. No real users take part. Instead, evaluators rely on heuristics, checklists, or cognitive models to predict where problems will occur. Lewis and Sauro [2021, page 977] list five common inspection methods, including:

- *Heuristic Evaluation*: Experts evaluate interfaces against a small set of usability principles.
- *Guideline Review*: Evaluators check compliance with specific interface standards.
- *Cognitive Walkthrough*: Evaluators simulate a user’s problem-solving process at each step of a task.

4.2 Usability Testing Methods

Usability testing methods collect data from test users who represent the target audience. Two of the most common usability testing methods are Thinking Aloud (TA) tests and formal experiments. A *thinking aloud test* is a formative testing method, where test users are asked to think out loud as they explore an interface with the goal of identifying usability issues. A *formal experiment* is a summative testing method, where measurements are taken and analysed statistically. Lewis and Sauro [2021, pages 976–977] refer to this category of methods as *user-based methods*. They identify seven common approaches, including:

- *Usability Testing*: Observers watch participants perform tasks with a product in a controlled environment (this encompasses both TA tests and formal experiments).

- *Surveys*: Questionnaires capture user satisfaction and perceived usability.
- *Card Sorting*: Users organise and categorise information, informing navigation structure.
- *A/B Testing*: Metrics from real web site users who experience slightly different interface variants are analysed for statistically significant differences.

What sets usability testing methods apart is that the evidence comes from real users working with the system [Hornbæk et al. 2025, page 714]. Such evidence is strong, but takes significant effort to gather. Hornbæk et al. [2025, page 719] describe these methods as labour-intensive and costly, because participants have to be recruited, sessions have to be run, and the data has to be analysed afterwards.

4.3 Heuristic Evaluation

In a heuristic evaluation, one or more evaluators step through an interface and compare what they see against a short set of usability principles [Wilson 2014, page 2]. The interface under review can be a specification, a prototype, or a finished product.

4.3.1 Nielsen's Ten Usability Heuristics

The most commonly used set of heuristics began as nine principles published in 1990 by Molich and Nielsen [1990]. In 1994, Nielsen reworked them by analysing 249 usability problems [Nielsen 1994], and arrived at the set of ten heuristics still in use today. Nielsen has since updated the definitions and examples, and now provides convenient one-page PDFs for each of the ten heuristics [Nielsen 2024]. They are listed below, quoted verbatim from Nielsen [2024].

1. *Visibility of System Status*: “The design should always keep users informed about what is going on, through appropriate feedback within a reasonable amount of time.”
2. *Match Between the System and the Real World*: “The design should speak the users’ language. Use words, phrases, and concepts familiar to the user, rather than internal jargon. Follow real-world conventions, making information appear in a natural and logical order.”
3. *User Control and Freedom*: “Users often perform actions by mistake. They need a clearly marked ‘emergency exit’ to leave the unwanted action without having to go through an extended process.”
4. *Consistency and Standards*: “Users should not have to wonder whether different words, situations, or actions mean the same thing. Follow platform and industry conventions.”
5. *Error Prevention*: “Good error messages are important, but the best designs carefully prevent problems from occurring in the first place. Either eliminate error-prone conditions, or check for them and present users with a confirmation option before they commit to the action.”
6. *Recognition Rather than Recall*: “Minimize the user’s memory load by making elements, actions, and options visible. The user should not have to remember information from one part of the interface to another. Information required to use the design (e.g. field labels or menu items) should be visible or easily retrievable when needed.”
7. *Flexibility and Efficiency of Use*: “Shortcuts — hidden from novice users — may speed up the interaction for the expert user so that the design can cater to both inexperienced and experienced users. Allow users to tailor frequent actions.”
8. *Aesthetic and Minimalist Design*: “Interfaces should not contain information that is irrelevant or rarely needed. Every extra unit of information in an interface competes with the relevant units of information and diminishes their relative visibility.”

9. *Help Users Recognize, Diagnose, and Recover from Errors*: “Error messages should be expressed in plain language (no error codes), precisely indicate the problem, and constructively suggest a solution.”

10. *Help and Documentation*: “It’s best if the system doesn’t need any additional explanation. However, it may be necessary to provide documentation to help users understand how to complete their tasks.”

In practice, evaluators are free to identify problems which do not map directly to any particular heuristic.

4.3.2 The Evaluation Process

Following the procedure outlined by Andrews [2026a, Section 8.1], a good approach to performing a heuristic evaluation embraces five phases:

1. Preparation
2. Individual Evaluations
3. Aggregation
4. Severity Ratings
5. Debriefing and Report

In essence, each evaluator goes through the interface alone, so as not to influence one another. Wilson [2014, pages 2–3] identifies three approaches for the individual evaluations. In *object-based* evaluation, evaluators examine individual interface elements against the heuristics. In *task-based* evaluation, they follow specific user tasks through the interface. A *hybrid* approach combines both, first working through tasks, then reviewing individual elements. Evaluators are typically asked to identify both positive and negative findings.

Once the evaluators have submitted their findings, the evaluation manager aggregates the findings into a merged list of problems (negative findings) and a separate merged list of positives. Similar findings might be combined onto a single finding in the merged list.

At this point, the merged lists are typically sent back to the evaluators, who are asked to independently assign severity ratings to each problem (and positivity ratings to each positive). Hornbæk et al. [2025, page 726] suggest using three levels of severity. A *minor* problem holds the user up for a moment. A *serious* one costs the user a lot of time, but the task still gets done in the end. A *catastrophic* one stops the task from being finished at all. Andrews [2026a, Section 8.2] typically uses 5 levels of severity.

Different evaluators tend to find different problems. This *evaluator effect* is well documented [Wilson 2014, pages 4–5, 16]. Causes include different backgrounds, levels of expertise, knowledge of heuristics, and familiarity with the domain and users. Multiple evaluators are therefore recommended. A team of three to five is a sensible starting point, and the right number depends on how complex the interface is and how experienced the evaluators are. The evaluator effect can be mitigated by training evaluators on the method and materials, providing realistic scenarios and background on the users, and using a common form for reporting results.

Wilson [2014, pages 8–11] summarises the strengths and weaknesses of a heuristic evaluation:

- + The method is simple to explain and relatively fast.
- + It needs no usability laboratory and no other special equipment.
- + No users need to be recruited.
- + It can be applied at any stage of development, from specifications to working products.

- + Team members who participate learn to recognise usability problems earlier.
- The evaluator effect (Section 4.3) leads to variable results.
- It copes badly with large interfaces that have many features and states.
- Evaluators are not actual users. Experts may miss problems that only arise during real use.
- It is often said to produce false positives, that is, reported problems which real users never run into, although the evidence for this is mixed (Section 4.4.5).
- Evaluators report problems at different levels of granularity.
- Results depend on evaluator quality and experience.

4.4 Thinking Aloud Testing

In thinking aloud (TA) testing, representative test users verbalise their thoughts while performing tasks with a system. Participants are asked to say out loud whatever goes through their mind at each step. Hornbæk et al. [2025, page 747] consider it unmatched among evaluation methods for revealing what goes on inside a user's mind during interaction.

4.4.1 Theoretical Foundation

As described by Lewis and Sauro [2021, page 982], the theoretical basis comes from Ericsson and Simon's work on verbal protocol analysis [Ericsson and Simon 1980]. Over time, practitioners developed their own best practices for thinking aloud testing, which are collected and described by Boren and Ramey [2000]. When participants explain why they chose an action or why something confused them, the evaluator gains clues about both the cause and possible fixes. Stricter protocols yield cleaner data but thinner insights. More relaxed protocols yield richer data but risk influencing the behaviour they aim to observe [Hornbæk et al. 2025, page 745].

4.4.2 Concurrent and Retrospective Thinking Aloud

Two main variants of TA exist. In *concurrent* TA, participants verbalise their thoughts continuously while performing tasks. In *retrospective* TA, participants work silently while being recorded, then review the recording and describe their thoughts afterwards. Thus, it avoids any influence on task performance, but requires at least twice as much time for data collection [Lewis and Sauro 2021, pages 982–983].

Alhadreti and Mayhew [2018, page 10] compared concurrent, retrospective, and hybrid TA on a library web site. Overall, the concurrent method came out ahead of the retrospective variant. It uncovered more problems than the retrospective method, while against the hybrid method it came out level. It also cost the evaluator far less time, because the other two protocols doubled the testing and analysis effort.

Whether thinking aloud affects task performance is debated. Some studies found no measurable difference between a think-aloud group and a silent group. Others reported better performance when participants verbalised their thoughts, possibly because articulating each step imposed useful structure on their reasoning [Lewis and Sauro 2021, pages 982–983]. The effect therefore depends on how the participants are instructed and on how hard the task is.

4.4.3 Practical Considerations

In classic thinking aloud, Ericsson and Simon asked the facilitator to prompt the participant to keep talking after a period of silence of around 30 seconds, and to think aloud as if they were alone in the room [Hornbæk et al. 2025, pages 744–745]. Boren and Ramey [2000, pages 268–270] proposed an alternative rooted in speech communication. The facilitator makes clear that the system is under test and not the participant, casts the participant as the domain expert and primary speaker, and keeps the conversation going with acknowledgement tokens such as “mm hm” and “uh-huh”. A third variant, relaxed thinking aloud, invites explanations and reflections. Hertzum et al. [2009, page 165] found that more relaxed TA changes visual search behaviour, navigation behaviour, and mental workload compared with the classic protocol.

For a TA test, it is important to create the right tasks, Hornbæk et al. [2025, pages 745–746] list several recommendations for TA tasks:

- Early tasks should be straightforward. Participants need to become comfortable with verbalising, before encountering difficult interactions.
- Task descriptions should reflect users real user activities, not system terminology. Using system-specific terms acts as hidden help.
- Completion criteria should be clear, so evaluators can tell whether participants realise they are done.
- Open-ended tasks can increase realism, for example asking about travel plans rather than specifying a fixed itinerary.

As detailed by Hornbæk et al. [2025, page 748], a 2020 survey of 197 usability professionals by Fan et al. [2020] found that 86% use TA in their tests, with 61% preferring concurrent TA. They further note that practice often deviates from the recommendations. Most respondents almost never ask participants to practice thinking aloud before the session, and many pose leading prompts such as asking participants to talk about their emotions. These deviations make it harder to compare results across studies and reduce the reliability of the findings.

4.4.4 Analysing Thinking Aloud Data

Analysis of TA data often follows three phases [Hornbæk et al. 2025, page 746]: preprocessing, identification, and synthesis. In the *preprocessing* phase, the evaluator transcribes and segments the verbal data. They optionally combine it with video, eye-tracking, or interaction logs.

In the *identification* phase, usability-relevant episodes are marked and classified. Separating transcription from interpretation allows different people to perform each step, which makes it possible to assess reliability across raters. Classification can proceed bottom-up (grouping observations by frequency or theme) or top-down (applying an existing coding scheme). Hornbæk et al. [2025, page 746] distinguish three main types of usability problem:

- *Failure to reach the goal*: The participant abandons the task, runs out of time, or ends up with an outcome that does not match the task description.
- *Misunderstandings about the system*: The participant has a clear goal but selects an incorrect action, or reacts with surprise when the interface behaves differently from what they anticipated.
- *Negative experience*: The participant verbalises frustration, explicitly labels something as a problem, or expresses dissatisfaction.

In the *synthesis* phase, problems are aggregated across participants and translated into redesign recommendations. The evaluator effect applies here as well. It was found, that only about 20% of usability problems were identified by all four evaluators in their study, while roughly half were found by just one

	Heuristic Evaluation	Thinking Aloud
Participants:	Expert evaluators.	Representative test users.
Timing:	Any stage of development.	Working prototype required.
Data Source:	Expert judgement.	User behaviour and commentary.
Main Output:	List of assessed problems.	List of observed problems.
Risk:	Predictions need confirming.	Narrow focus on given tasks.

Table 4.1: Heuristic evaluation versus thinking aloud testing.

evaluator [Hornbæk et al. 2025, page 747]. Using a shared coding scheme and having multiple analysts review the same transcripts can reduce this variability.

4.4.5 Comparison with Heuristic Evaluation

As Hornbæk et al. [2025, page 721] discuss, numerous researchers have compared usability inspection methods with usability testing methods. Heuristic evaluation (a formative inspection method) and thinking aloud testing (a formative testing method) are two of the most widely used formative methods. Table 4.1 summarises the key differences between the two approaches.

These methods can produce similar but different results. For example, expert evaluators may flag issues which never affect real users, while users may stumble over problems which experts overlook. Molich [2018] ran a series of ten studies looking at how methods of usability evaluation were used in practice, the Comparative Usability Evaluation (CUE) studies [Molich 2026]. In particular, the CUE-4 study [Molich and Dumas 2008] compared the results of heuristic evaluation and thinking aloud testing. Seventeen experienced professional teams evaluated the same web site (www.hotelpenn.com), nine of them using usability testing and eight using expert reviews. The teams reported 340 distinct issues, of which only nine were named by more than half of the teams, while 205 issues, or 60%, came from a single team alone, and 61 of those were rated serious or critical. A single evaluation of either kind covers only part of the problem space: the overlap between independent evaluations is small. The evaluator effect described in Section 4.3 pulls in the same direction. Neither method, on this evidence, surveys the whole of an interface on its own.

Whether heuristic evaluation raises false alarms is disputed. Molich and Dumas [2008, page 280] conclude that “false alarms are not the problem that some have claimed”. Their reviewers were seasoned practitioners, however, and Molich [2018, page 84] notes that the one place in the series where false alarms did surface was CUE-3, where reviewers with less experience took part.

What the two methods share matters more here than what divides them. Both accept that one evaluation sees only part of an interface, and that what it sees depends on who carries it out. That is a good argument for running both a heuristic evaluation and a thinking aloud test, rather than just one of them.

Chapter 5

PCEE: Thinking Aloud Test Plan

This chapter presents the test plan which was prepared for the thinking aloud test of PCEE. The corresponding report of the test itself is presented in Chapter 6. The test plan is also available online [Zollner 2025c].

5.1 Introduction

The Parallel Coordinates Explorable Explainer (PCEE) is an interactive tutorial about the parallel coordinates visualisation technique for multidimensional datasets. It is designed for newcomers to the topic to learn the basics about parallel coordinates and become familiar with this kind of graphical chart. PCEE is an open-source project [Andrews and Gruber 2026a]. A live version of the web application is hosted at [Andrews and Gruber 2026b].

The web application is available only in English and will be tested in English with English-speaking test users. The evaluation will cover the entire PCEE web application. A separate branch will be created for the thinking aloud tests, so as to preserve the exact version used.

5.2 Test Methodology

A thinking aloud (TA) test is a usability testing method that asks test users to talk out loud as they work. As Nielsen [2012] defines it, participants use the system and continuously verbalise their thoughts as they move through the interface. Test users should perform their tests independently of one another. The thinking aloud method is described in detail by Barnum [2021].

Before starting the tasks, each user will be asked to fill out a consent form. Any questions about data collection will be answered, and then the user's background data will be collected by the facilitator in the form of a background questionnaire. Each test user will be shown a short video on how to think aloud, and will then practise thinking out loud with one or two training tasks.

For the first task, the user will be asked to work through the interactive tutorial provided by PCEE. Afterwards, five smaller, more specific tasks will be given, to cover workflows which may be used less frequently. Once the tasks have been completed, a short interview will be conducted and the test user will be asked to fill out a feedback questionnaire.

After all five test users have completed their tests, the facilitator's notes and session recordings will be analysed and positive findings and negative findings (problems) will be extracted with corresponding illustrative video clips. Then, the findings will be aggregated into separate lists of positive and negative findings. Finally, ratings for positivity and severity will be assigned by members of the project team, and the lists will be sorted in decreasing order of positivity and severity, respectively.

Test User	TP1 (Pilot)	TP2	TP3	TP4	TP5
Alias:	“Peter”	“Bob”	“Julian”	“James”	“Robert”
Gender:	male	male	male	male	male
Age:	23	32	20	23	24
Education:	Bachelor, studying Information Security	Master, working in software engineering/sales	A Levels, working in financial consulting	A Levels, working in financial consulting	A Levels, studying Physics
Language of Test:	EN	EN	EN	EN	EN
Planned Date of Test:	03 Dec 2025	04 Dec 2025	05 Dec 2025	06 Dec 2025	07 Dec 2025
Planned Time of Test:	09:00	18:00	17:00	15:00	14:00

Table 5.1: Overview of the planned test users.

Device:	HP Elitebook 840 G10
OS and Version:	Debian 13
Screen Size:	14"
Screen Resolution:	1920×1200
Web Browser and Version:	Chromium 143.0.7499.169
Internet Connection:	4G 100 Mbps
Screen Recording Software:	OBS Studio 32.0.4
Recording Resolution:	1920×1200

Table 5.2: Planned environment for the thinking aloud tests.

5.3 User Profiles

Two user profiles were identified for PCEE:

- *Students in an InfoVis class:* PCEE can be used as lecture material and as an interactive tool during class to demonstrate the concept of parallel coordinates, which can be revisited by students at home.
- *Independent Study:* PCEE can be accessed online, so it is available to a wide audience for “independent study”.

5.4 Test Users

Table 5.1 gives an overview of the test users planned to participate in the study.

5.5 Test Environment

All users will use the same test environment for the thinking aloud test. The planned environment for the tests is shown in Table 5.2.

For this test, no ad blocker will be used. PCEE does not require any cookies. The browser data will be cleared before each test to provide a clean environment for each user.

5.6 Recording

For external video recording, a Sanyo Xacti HD1010 video camera will be mounted on a tripod and used to film over the user's right shoulder. A mirror will be placed to the left of the laptop screen. The camera's field of view will be set up to capture the screen, keyboard, and user's facial expressions in the mirror. A DeLOCK 66640 table microphone will be used to capture audio for the external recording.

For session capture, OBS Studio 32.0.4 will be used to record the screen, audio, and the user's face. The laptop's internal webcam will provide audio and video of the user's face, with the facecam video window placed in the bottom left corner of the screen.

Video clips will be extracted from the session recordings to illustrate findings for the report using Kdenlive 24.12.3. The same software will be used to pixelate the faces of the test users and to transcode the video clips where necessary.

5.7 Training

First, a small video clip of how to conduct a thinking out loud test will be shown. To practise thinking out loud, users will then be asked to perform one or two tasks on YouTube. The first training task will be to find a video of dog food. The second training task will be to find a German rap song on YouTube Music.

5.8 Test Tasks

Table 5.3 shows the tasks which will be used to test PCEE.

5.9 Interview Questions

The following questions will be asked of each user immediately after the final task:

- *Opening Question*
 - “How was it?”
- *Standard Questions*
 - “Did anything strike you as particularly good?”
 - “Did anything strike you as particularly bad?”
 - “Do you now know what parallel coordinates are?”
- *Individual Questions:* If any questions come up during the test with a test user, the user will be asked those questions at this point.

5.10 Data Collection and Collation

The consent form which test users will be asked to read and sign can be found in Appendix A.3. For the background questionnaire, found in Appendix A.4, the facilitator will ask the questions of the user and fill out the form, rather than handing the form to the user to fill out. Any questions regarding data collection will be answered before the start of the recording. Once all tasks are finished, the test user will be handed a feedback questionnaire to fill out, which can be found in Appendix A.7.

In any retained data, all test users will be referred to by a first name alias and a test user ID. All personally identifiable data will be deleted within one year.

The materials prepared by the test team for this plan are: checklist, orientation script, background questionnaire, consent form, task slips, and feedback questionnaire, which are provided in Appendix A.

Task No.	Description	Short Title	Prerequisites	Completion Criteria	Max. Time	Possible Solution Path
1	Please work your way through the tutorial about Parallel Coordinates.	Work Through Tutorial	Browser is open at localhost.	The user indicates that they have finished the tutorial.	25 minutes.	–
2	Go to Section 7 Case Study: Student Marks. In the final step (Step 6), enable interactivity, so you can explore the dataset. Do some analysis to check whether there may be a correlation between student marks in Maths and IT.	Simple Correlation	–	The user indicates that there is a correlation.	10 minutes.	Section 7 → 6. Explore the Data → Enable Interactivity → Move IT next to Maths → reverse IT
3	Go to Section 2 Personal Finances dataset. Add some extra data to the dataset using the table and see how that affects the chart.	Add Extra Data	–	–	10 minutes.	Section 2 → Add a row → Add a column → Add some data that is not 0
4	Go to Section 2 Personal Finances dataset. Let the range of the Income and Costs columns start at 0.	Set Range	–	The user set the range starting points of Income and Costs to 0.	10 minutes.	Section 2 → Right click on the cost dimension → Set Range → Set Min: 0 → Save → Right click on the income dimension → Set Range → Set Min: 0 → Save
5	Go to Section 2 Personal Finances dataset. Download an image of the chart.	Download Image	–	The user downloaded an image of the chart.	10 minutes.	Section 2 → Double arrow menu → Download Chart (SVG) → Download
6	Go to Section 5 Heart Health dataset. Download the table as a CSV file to work with it in Excel.	Download CSV	–	The user downloaded the data as a CSV file.	10 minutes.	Section 5 → Double arrow menu → Show Table → Save as CSV

Table 5.3: The internal task list for use by the test team.

Chapter 6

PCEE: Thinking Aloud Test Report

This chapter presents the usability test report for PCEE. The study involved a thinking aloud (TA) test with a representative group of five novice users, complementing the heuristic evaluation by expert reviewers described in [Zollner 2025b]. The thinking aloud report is also available online as an HTML document [Zollner 2026].

6.1 Executive Summary

The Parallel Coordinates Explorable Explainer (PCEE) is a web application which provides an interactive tutorial about the parallel coordinates visualisation technique for multidimensional data. Five test users from the user group “independent study” participated in a thinking aloud study to evaluate the web application. As Nielsen [2012] explains, a thinking aloud test asks participants to use the system while continuously verbalising their thoughts as they move through the interface. Notes were taken by the facilitator and each evaluation session was recorded. Afterwards, the notes and recordings were analysed and assembled into two lists of findings: positives and negatives (problems). The findings were then assigned severity ratings by three members of the project team and were ordered by mean severity. The full report is also available online [Zollner 2026].

Three positive findings were made. The first, mentioned by two of the test users, is that the values corresponding to a polyline on every dimension are displayed when hovering over it. The second positive finding, mentioned by one test user, is that the mouse cursor changes when hovering over a possible action. The third positive finding, which one test user mentioned, is that, in the interactive table at the start, Tab can be used to jump to the next cell in a row.

Eleven negative findings (problems) were collected and then sorted by mean severity. The most severe problem, mentioned by three of the test users, was that it was impossible to redraw the chart in Section 2 when 0 was entered as a value in the table, because the Redraw Chart button is greyed out. The second most severe finding, mentioned by two of the test users, was that the chart in Section 7 is very packed with records, so it can be difficult to trace a single polyline throughout the chart. The possibility of zooming within the chart would have mitigated this problem. The third most severe finding, mentioned by four of the test users, was that the context menu was poorly described. Four out of five test users had difficulties finding the context menu, and the fifth found it only after receiving help. The full set of findings is described in the body of the report.

Based on the post-test interviews and feedback questionnaire responses, the test users enjoyed working through PCEE, and successfully gained an understanding of the parallel coordinates technique.

6.2 Introduction

The Parallel Coordinates Explorable Explainer (PCEE) is an interactive tutorial about the parallel coordinates visualisation technique for multidimensional datasets. It is designed for newcomers to the topic to learn the basics about parallel coordinates and become familiar with this kind of graphical chart. In PCEE, users typically switch back and forth between the explanatory text and interactive elements. For further analysis in external applications, the featured datasets can be downloaded in CSV format. PCEE is an open-source project [Andrews and Gruber 2026a]. A live version of the web application is hosted at [Andrews and Gruber 2026b].

The web application is available only in English and was tested in English with English-speaking test users. The evaluation covered the entire PCEE web application, with the specific branch “Test-2025-12-03” being used by all test users.

6.3 Test Procedure

The following procedure was used to conduct the thinking aloud test.

6.3.1 Test Methodology

A thinking aloud test is a usability testing method that depends on the verbalisation of the thoughts of test users. As Nielsen [2012] defines it, participants are asked to use the system and to keep saying out loud what they think as they move through the interface. Test users generally perform their tests independently of one another.

There are two ways of conducting thinking aloud. In concurrent TA, test users are encouraged to speak out loud while working on the provided tasks, whereas in retrospective TA they are asked about their thoughts and experiences after the tasks. Research has shown concurrent TA to be more effective [Alshammari et al. 2015], and it was used in this study.

For this test, a short training in thinking aloud was provided before the start of each test, so test users could practise verbalising their thoughts. Changes in speech rate, volume, and pitch can indicate usability problems, in addition to negative remarks. The thinking aloud method is described in detail by Barnum [2021].

Before starting the tasks, each test user was asked to fill out a consent form. Any questions about personal data collection were answered, and then the user’s background data was collected by the facilitator in the form of a background questionnaire. Each test user was shown a short video on how to think aloud, and then thinking out loud was practised with one or two training tasks.

For the first task, the users were asked to work through the interactive tutorial provided by PCEE. Afterwards, five smaller more specific tasks were given, to cover workflows which may be used less regularly. Once the tasks were completed, a short interview was conducted and the test users were asked to fill out a feedback questionnaire.

After all five test users had completed their tests, the facilitator’s notes and session recordings were analysed and positive findings and negative findings (problems) were extracted with corresponding illustrative video clips. Then, the findings were aggregated into separate lists of positive and negative findings. Finally, ratings for positivity and severity were assigned by members of the project team, and the lists were sorted in decreasing order of positivity and severity respectively.



Figure 6.1: Photo of the test room.

6.3.2 User Profiles

Two user profiles were identified for PCEE:

- *Students in an InfoVis class:* PCEE can be used as lecture material and as an interactive tool during class to demonstrate the concept of parallel coordinates, which can be revisited by students at home.
- *Independent Study:* PCEE can be accessed online, so it is available to a wide audience for “independent study”.

The goals of both user groups are identical. Users of PCEE want to learn about parallel coordinates by working through an interactive tutorial. All tested users fell into the category of “independent study”.

6.3.3 Test Users

Test users were selected with the minimum requirement of being fluent in the English language, having a basic understanding of maths, wanting to learn new tools or concepts, and having no prior knowledge about parallel coordinates. These criteria were confirmed in a short screening check a week before the tests.

Table 6.1 gives an overview of the test users who participated in the study. First name aliases are used throughout this report to protect their identity.

6.3.4 Test Environment

The test room is shown in Figure 6.1. The environment used for the thinking aloud tests is shown in Table 6.2. Test users worked on a laptop with its integrated touchpad, no mouse was provided.

The exact web browser version used for the tests is shown in Figure 6.2. During the tests, no ad blocker was used and cookie selection was left to the user. This was only relevant for the training, because the web application does not store any cookies.

To record the external videos, a Sanyo Xacti HD1010 camcorder was mounted on a tripod and connected to a DeLOCK 66640 Stereo Table Microphone. In order to see the facial expressions of the test user in

Test User	TP1 (Pilot)	TP2	TP3	TP4	TP5
Alias:	“Peter”	“Bob”	“Julian”	“James”	“Robert”
Date of Test:	03 Dec 2025	04 Dec 2025	05 Dec 2025	06 Dec 2025	07 Dec 2025
Time of Test:	10:00	20:15	17:45	15:00	14:10
General Information					
Gender:	male	male	male	male	male
Age:	23	32	20	23	24
Occupation:	Student at TU Graz	Software Engineer/Sales	Financial Consultant	Financial Consultant	Student at TU Vienna
Education					
Highest Level:	Bachelor	Master	A Levels	A Levels	A Levels
Area of Study:	Information Security	Mechanical Engineering & Computer Science	–	Physics	Physics
Personal Computer Usage					
Kind of PC:	Linux	Windows	Windows	MacOS	Linux
Years of Experience:	12	25	6	15	11
Hours per Week:	60	50	56	56	7
Tablet Usage					
Kind of Tablet:	None	None	None	iPadOS	iPadOS
Years of Experience:	–	–	–	7	3
Hours per Week:	–	–	–	14	35
Smartphone Usage					
Kind of Smartphone:	Android	Android	Android	iOS	Android
Years of Experience:	12	15	9	10	13
Hours per Week:	10	7	35	14	10.5
Web Usage					
Hours per Week:	70	57	35	56	28
Mostly Used Device:	Laptop	Laptop	Smartphone	Laptop	Tablet
Internet Connection:	cable modem	fibre optic	5G	5G	fibre optic
Web Browser:	Firefox	Firefox	Chrome	Safari	Firefox
Experience as Web Site Admin:	2	None	None	None	None
Domain-Specific Questions					
Knowledge of ParCoord:	No	No	No	No	No
Data Analysis Tools:	Excel	Excel/Numpy	Excel	Excel	Excel
Use of Interactive Tutorials:	Yes	Yes	No	Yes	No
Previous Usability Tests					
As Test Person:	Yes	No	No	No	No
In Project Team:	Yes	No	No	No	No
Type of Test:	TA	–	–	–	–

Table 6.1: Overview of the test users.

Device:	HP Elitebook 840 G10, 32 GB RAM
OS and Version:	Debian 13
Screen Size:	14" TFT
Screen Resolution:	1920×1200
Web Browser and Version:	Chromium 143.0.7499.169
Internet Connection:	A1 LTE 4G Hotspot
Download Speed:	100 Mbps
Screen Recording Software:	OBS Studio 32.0.4
Recording Resolution:	1920×1080
Video Editing Software:	Kdenlive 24.12.3
Video Transcoding Software:	Kdenlive 24.12.3

Table 6.2: Environment used for the thinking aloud test.

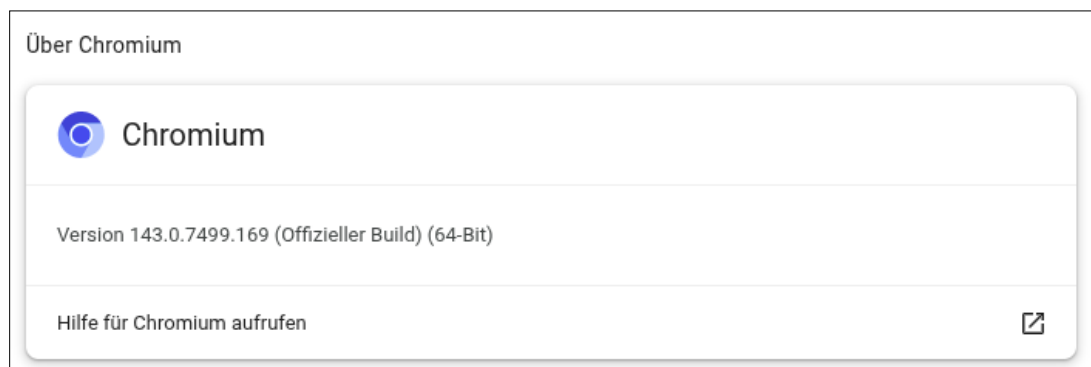


Figure 6.2: Browser version used for the tests.

the external video recordings, a mirror was placed to the left of the laptop screen and the camera was positioned to record over the user's right shoulder. The integrated webcam and microphone of the laptop were used to overlay the user's face in the bottom left corner of the session capture video.

6.3.5 Training

To practise thinking aloud, the user was first asked to navigate to YouTube and search for a video of dog food. After finding a video, the user was asked to navigate to YouTube Music and search for a German Rap song, all the time while talking aloud.

6.3.6 Tasks

The internal task list used by the project team is shown in Table 6.3.

6.3.7 Interview Questions

Each user was interviewed immediately after the final task using the interview script given in Appendix A.6. Summaries of the interviews can be found in Section 6.4.6.

Task No.	Description	Short Title	Prerequisites	Completion Criteria	Max. Time	Possible Solution Path
1	Please work your way through the tutorial about Parallel Coordinates.	Work Through Tutorial	Browser is open at localhost.	The user indicates that they have finished the tutorial.	25 mins.	–
2	Go to Section 7 Case Study: Student Marks. In the final step (Step 6), enable interactivity, so you can explore the dataset. Do some analysis to check whether there may be a correlation between student marks in Maths and IT.	Simple Correlation	–	The user indicates that there is a correlation.	10 mins.	Section 7 → 6. Explore the Data → Enable Interactivity → Move IT next to Maths → reverse IT
3	Go to Section 2 Personal Finances dataset. Add some extra data to the dataset using the table and see how that affects the chart.	Add Extra Data	–	–	10 mins.	Section 2 → Add a row → Add a column → Add some data that is not 0
4	Go to Section 2 Personal Finances dataset. Let the range of the Income and Costs columns start at 0.	Set Range	–	The user set the range starting points of Income and Costs to 0.	10 mins.	Section 2 → Right click on the cost dimension → Set Range → Set Min: 0 → Save → Right click on the income dimension → Set Range → Set Min: 0 → Save
5	Go to Section 2 Personal Finances dataset. Download an image of the chart.	Download Image	–	The user downloaded an image of the chart.	10 mins.	Section 2 → Double arrow menu → Download Chart (SVG) → Download
6	Go to Section 5 Heart Health dataset. Download the table as a CSV file to work with it in Excel.	Download CSV	–	The user downloaded the data as a CSV file.	10 mins.	Section 5 → Double arrow menu → Show Table → Save as CSV

Table 6.3: Internal task list used by the project team.

	Task 1	Task 2	Task 3	Task 4	Task 5	Task 6
TP1	1*	1	0	1	1	1
TP2	1	1	1	1	1	1
TP3	1	1	1	0	0	1
TP4	1	1	1	0	1	1
TP5	1	1	1	1	1	1
Total	5	5	4	3	4	5
%	100	100	80	60	80	100

Table 6.4: Task completion rates. An asterisk (*) indicates that assistance was given.

6.3.8 Feedback Questionnaire

After the interview, the user was asked to fill out the feedback questionnaire given in Appendix A.7. The feedback questionnaire was given on paper. An overview of the results can be seen in Section 6.4.7.

6.3.9 Data Collection

Before starting the tests, the test users were given a short introduction. Then, they were given a consent form to read and sign, which can be found in Appendix A.3. For the background questionnaire, found in Appendix A.4, the facilitator asked the questions of the user and filled out the form, rather than handing the form to the user to fill out. Any questions regarding data collection were answered before the start of the recording. Once all tasks were finished, the test user was handed a feedback questionnaire to fill out, which can be found in Appendix A.7. The complete set of materials used by the project team is provided in Appendix A, and the background and feedback questionnaires completed by each test user are reproduced in Appendix B.

All video clips, which are provided with the online version of this report [Zollner 2026], have pixelated faces to protect the privacy of the test users. The pixelation was performed with Kdenlive. All test users and their data are identified with a first name alias or a unique test person ID.

The mapping of user aliases, the signed consent forms, and the full session videos contain personally identifiable data of the test users. These files are not part of this report, are kept separate from non-identifiable data, and will be deleted within one year.

6.4 Results

The results of the TA test comprise task completion statistics, positive and negative findings, summaries of interviews with the test users, and an overview of the ratings given by users in the feedback questionnaire. Due to a technical error, all video clips containing TP1 were extracted from the external video rather than the session capture video.

6.4.1 Task Completion

A summary of which users completed each task and whether any assistance was given is shown in Table 6.4.

Positivity	Meaning
4	Extremely Positive
3	Major Positive
2	Minor Positive
1	Cosmetic Positive
0	Not a Positive

Table 6.5: Positivity ratings.

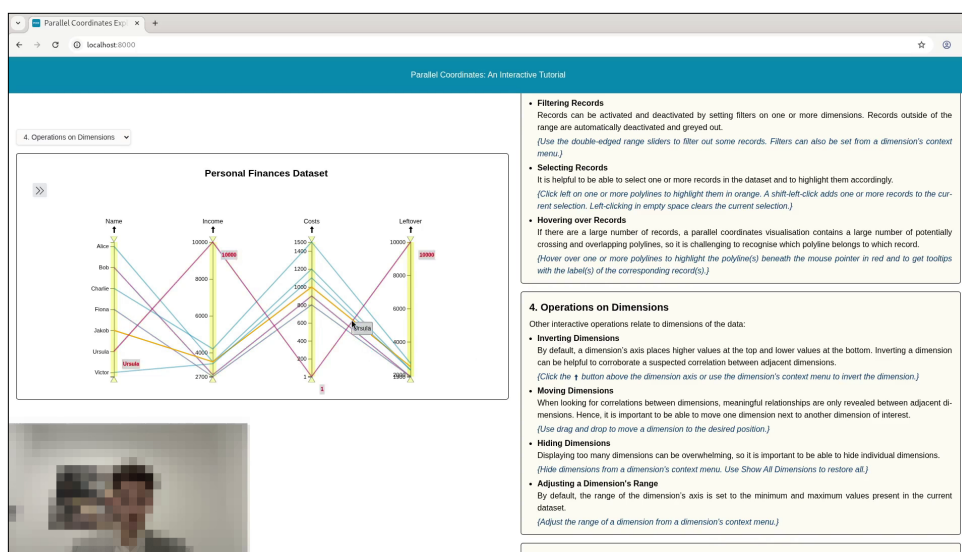


Figure 6.3: When hovering over a polyline the corresponding values are displayed.

6.4.2 Top Three Positive Findings

The three most positive findings according to their average (mean) positivity ratings are described in more detail below. The positivity rating scheme used to rank positive findings is shown in Table 6.5.

P01. Values Shown when Hovering

Title:	Values Shown when Hovering
Description:	When hovering over a polyline in any chart, the corresponding values on all dimensions are displayed.
Video Clip(s):	p01-tp3-hovering-values.mp4, p01-tp4-hovering-values.mp4
Timestamp(s):	TP3 00:10:58, TP4 00:10:35
Location (How Reproducible?):	Go to any chart → Hover over a polyline
Mean Positivity:	3.67

The chart was praised for the functionality to see all corresponding values when hovering over a polyline as can be seen in Figure 6.3.

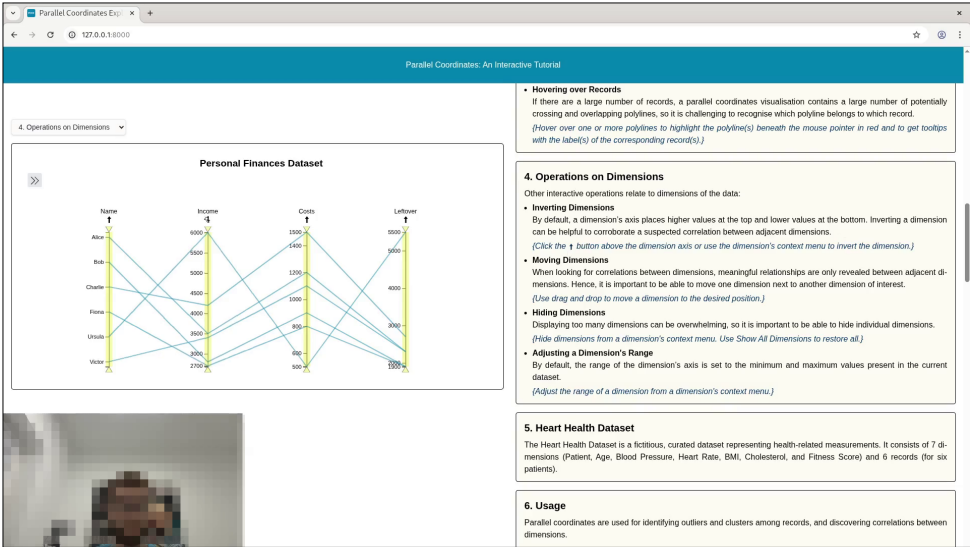


Figure 6.4: When hovering over a draggable or clickable object, the mouse cursor changes to indicate the possible action.

P02. Mouse Cursor Changes to Indicate Actions

Title:	Mouse Cursor Changes to Indicate Actions
Description:	When hovering over a draggable or clickable object, the mouse cursor changes to indicate the possible action.
Video Clip(s):	p02-tp2-cursor-change.mp4
Timestamp(s):	TP2 00:08:38
Location (How Reproducible?):	Go to any chart → Hover over the label of a dimension
Mean Positivity:	3.00

The chart actions were praised for the change of the mouse cursor when an object is clickable or draggable as can be seen in Figure 6.4.

P03. Tab Can Be Used to Advance in Table

Title:	Tab Can Be Used to Advance in Table
Description:	In Section 2, when entering a new value in the same row, the Tab key can be pressed to jump to the next field.
Video Clip(s):	p03-tp2-tab-to-advance.mp4
Timestamp(s):	TP2 00:20:43
Location (How Reproducible?):	Section 2 → click a field not in the last column → press Tab
Mean Positivity:	1.33

The table in Section 2 was praised for the option to jump to the next column when pressing the Tab key, as can be seen in Figure 6.5.

6.4.3 List of All Positive Findings

Table 6.6 shows a list of all the positive aspects observed in the test, sorted in decreasing order of average (mean) positivity, i.e. the most positive are at the top of the table. Positivity ratings were assigned by members of the project team. Their name codes are shown in Table 6.7.

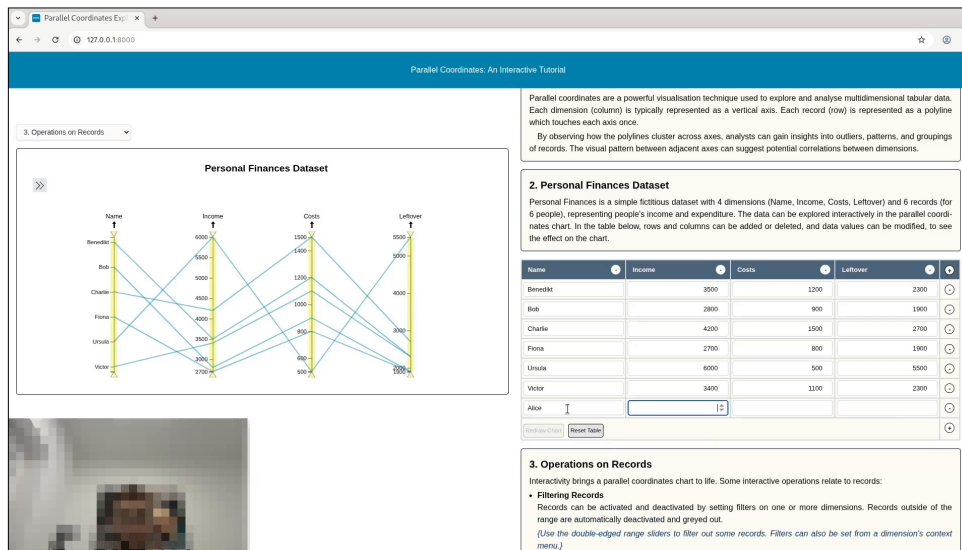


Figure 6.5: In the table in Section 2, pressing the Tab key can be used to jump to the next field.

No.	Title	Description	Location (how reproducible?)	KA	RG	FZ	Mean
1	Values Shown when Hovering	When hovering over a polyline in any chart, the corresponding values on all dimensions are displayed.	Go to any chart → Hover over a polyline	4	3	4	3.67
2	Mouse Cursor Changes to Indicate Actions	When hovering over a draggable or clickable object, the mouse cursor changes to indicate the possible action.	Go to any chart → Hover over the label of a dimension	3	3	3	3.00
3	Tab Can Be Used to Advance in Table	In Section 2, when entering a new value in the same row, the Tab key can be pressed to jump to the next field.	Section 2 → click a field not in last column → press Tab	2	1	1	1.33

Table 6.6: Aggregated list of all positive findings, in descending order of average (mean) positivity. Ratings were assigned by KA, RG, and FZ (see Table 6.7).

6.4.4 Top Five Problems

The five most serious problems according to their average (mean) severity ratings are described in more detail below. Problem number 1 is the problem (negative finding) with the highest mean severity. The severity rating scheme used to rank problems is shown in Table 6.8.

N01. Inserting 0 Into Table Not Possible

Title:	Inserting 0 Into Table Not Possible
Description:	In Section 2, it is not possible to redraw the chart after the value 0 is entered into the table, because the Redraw Chart button is greyed out.
Video Clip(s):	n01-tp1-insert-0.mp4, n01-tp3-insert-0.mp4, n01-tp4-insert-0.mp4
Timestamp(s):	TP1 00:17:28, TP3 00:07:44, TP4 00:26:04
Location (How Reproducible?):	Section 2 → Table → Change any value to 0 → Redraw Chart
Mean Severity:	3.00

Three test users discovered that the value 0 cannot be inserted into the chart by typing it into the table in Section 2, because the Redraw Chart button becomes disabled, as can be seen in Figure 6.6.

Code	Meaning
KA	Keith Andrews
RG	Romana Gruber
FZ	Florian Zollner

Table 6.7: Name codes.

Severity	Meaning
4	Catastrophic problem
3	Serious problem
2	Minor problem
1	Cosmetic problem
0	Not a problem

Table 6.8: Severity ratings.

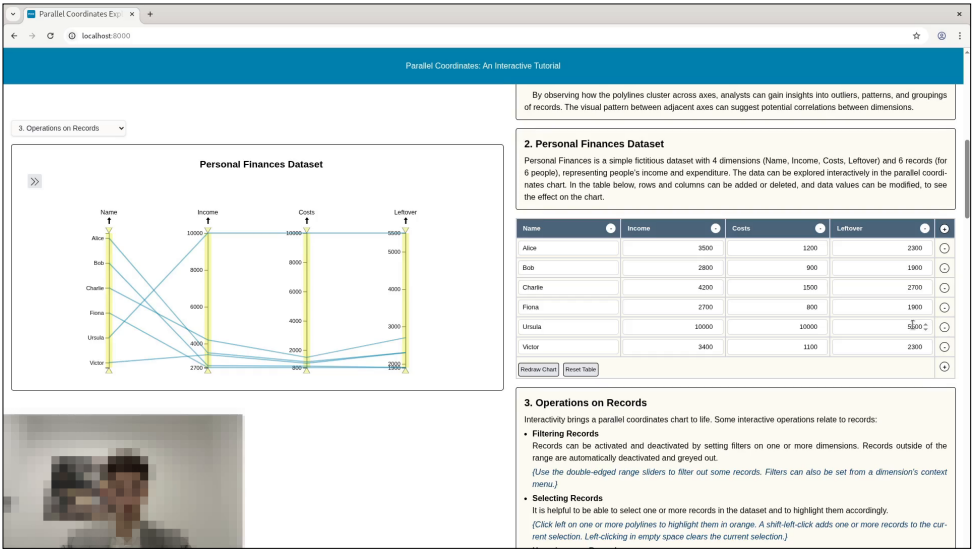


Figure 6.6: Inputting 0 into the table breaks functionality.

N02. Zooming Into Chart is Not Possible

Title:	Zooming Into Chart is Not Possible
Description:	In Section 7, it can be difficult to trace a single polyline or value. The ability to zoom in would be helpful.
Video Clip(s):	n02-tp3-chart-zoom.mp4, n02-tp4-chart-zoom.mp4
Timestamp(s):	TP3 00:32:07, TP4 00:21:20
Location (How Reproducible?):	Section 7 → Follow a polyline in a cluster through the chart
Mean Severity:	3.00

Selecting a single polyline, especially on a smaller screen, becomes more difficult as the number of polylines increases, as can be seen in Figure 6.7. This can be solved by introducing a zoom function.

N03. Context Menu Poorly Described

Title:	Context Menu Poorly Described
Description:	The context menu is referenced in Sections 3 and 4, but it is not described how to open the context menu.
Video Clip(s):	n03-tp2-context-menu.mp4, n03-tp3-context-menu.mp4, n03-tp4-context-menu.mp4, n03-tp5-context-menu.mp4
Timestamp(s):	TP2 00:09:24, TP3 00:13:14, TP4 00:13:03, TP5 00:10:46
Location (How Reproducible?):	–
Mean Severity:	2.67

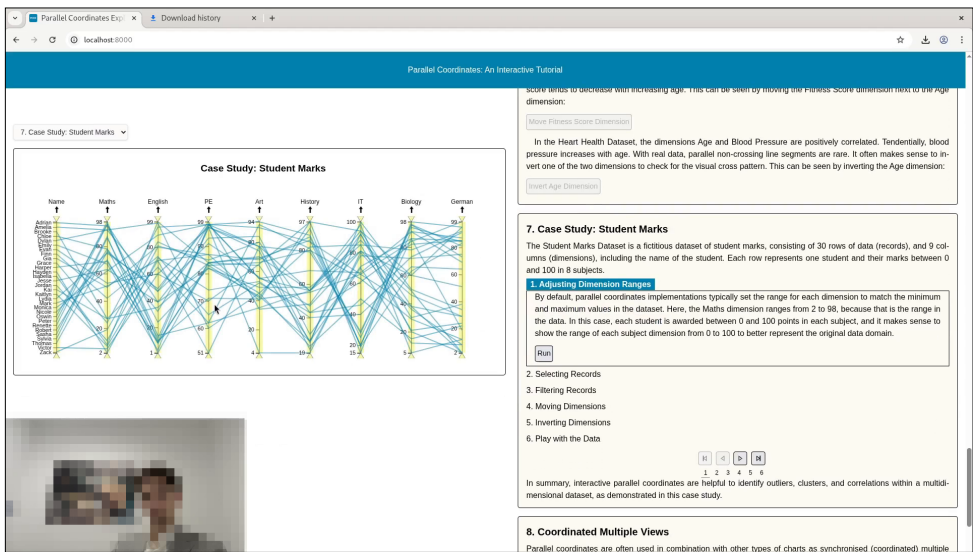


Figure 6.7: Selecting a single polyline can be difficult.

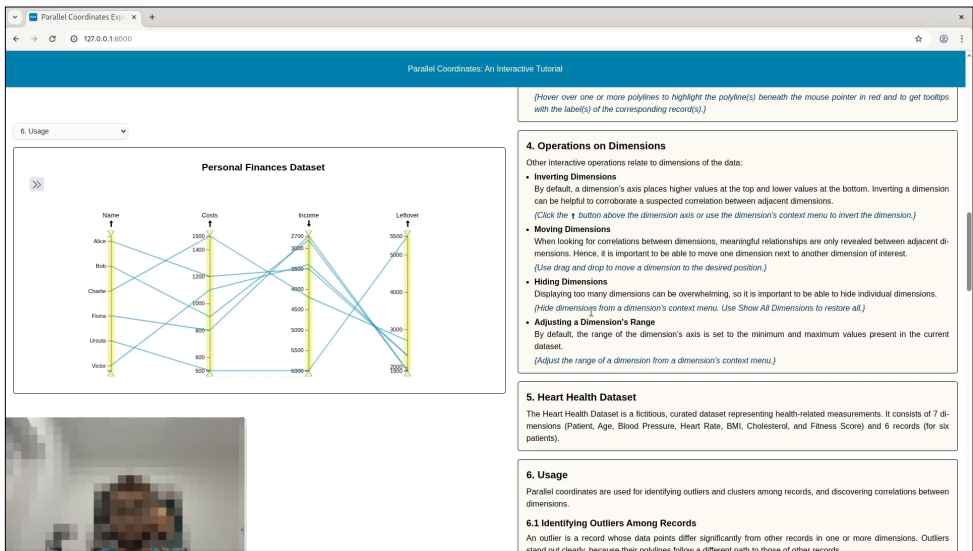


Figure 6.8: How to find the context menu is not explained.

Figuring out what and where the context menu is can be hard for a new user, as can be seen in Figure 6.8. This can be solved by adding an explanation.

N04. Polyline Selection Difficult

Title:	Polyline Selection Difficult
Description:	Selecting a polyline in any chart is only possible when directly hovering/clicking on the line, which can be difficult depending on the size of the chart and the number of polylines visible.
Video Clip(s):	n04-tp1-polyline-selection.mp4, n04-tp2-polyline-selection.mp4, n04-tp4-polyline-selection.mp4, n04-tp5-polyline-selection.mp4
Timestamp(s):	TP1 00:05:41, TP2 00:07:37, TP4 00:09:35, TP5 00:09:59
Location (How Reproducible?):	Go to any chart → Select one or more polylines
Mean Severity:	2.33

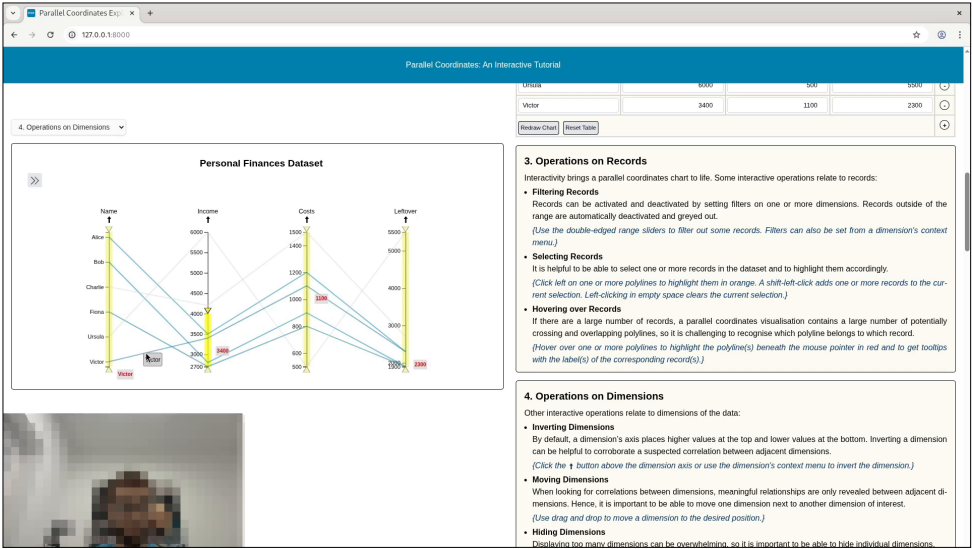


Figure 6.9: Selecting a polyline in a chart can be difficult.

Selecting one or more polylines can be hard as the area that is clickable is very small, as can be seen in Figure 6.9. This could be solved by increasing the size of a polyline’s hit surface.

N05. Case Study Interactivity Poorly Described

Title:	Case Study Interactivity Poorly Described
Description:	In Section 7, it is not explained how the user should interact with the case study and that interactive operations are disabled until Step 6.
Video Clip(s):	n05-tp2-case-study-interaction.mp4, n05-tp4-case-study-interaction.mp4, n05-tp5-case-study-interaction.mp4
Timestamp(s):	TP2 00:24:44, TP4 00:20:40, TP5 00:20:44
Location (How Reproducible?):	Section 7 → First paragraph → Only dataset is explained
Mean Severity:	2.33

The user is not informed what actions they should do during the case study, as can be seen in Figure 6.10. This could be solved by adding a short how-to part in the case study or nudging the user with well-known icons and smaller info texts.

6.4.5 List of All Problems Found

Table 6.9 shows a list of all the problems observed in the test, sorted in decreasing order of average (mean) severity, i.e. the most severe are at the top of the table. Severity ratings were assigned by members of the project team. Their name codes are shown in Table 6.10.

No.	Title	Description	Location (how reproducible?)	KA	RG	FZ	Mean
1	Inserting 0 into Table Not Possible	In Section 2, it is not possible to redraw the chart after the value 0 is entered into the table, because the Redraw Chart button is greyed out.	Section 2 → Table → Change any value to 0 → Redraw Chart	2	3	4	3.00
2	Zooming into Chart is Not Possible	In Section 7, it can be difficult to trace a single polyline or value. The ability to zoom in would be helpful.	Section 7 → Follow a polyline in a cluster through the chart	4	2	3	3.00
3	Context Menu Poorly Described	The context menu is referenced in Sections 3 and 4, but it is nowhere described how to open the context menu.	–	3	2	3	2.67
4	Polyline Selection Difficult	Selecting a polyline in any chart is only possible when directly hovering/clicking on the line, which can be difficult depending on the size of the chart and the number of polylines visible.	Go to any chart → Select one or more polylines	3	1	3	2.33
5	Case Study Interactivity Poorly Described	In Section 7, it is not explained how the user should interact with the case study and that interactive operations are disabled until Step 6.	Section 7 → First paragraph → Only dataset is explained	2	2	3	2.33
6	Filtering Icon Poorly Described	In Section 3, under “Filtering Records” it is verbally explained how to filter, but a graphic representation of the “double-edged range sliders” is missing and can be misinterpreted.	Section 3 → Filtering Records	3	2	2	2.33
7	Transition of Charts Not In Sync With Text	In Section 4, when scrolling down in the text, it can happen that the user is still reading text, while the chart has already switched to the Heart Health dataset.	Section 4 → scroll down until Section 5 is in the middle of the page	3	1	1	1.67
8	Touchpad Too Sensitive	The sensitivity of the touchpad was too high.	Open Web Application → scroll down	2	0	2	1.33
9	Toolbar Button Tooltips are Not Shown When Quickly Skimming Over	The meaning of the chart toolbar buttons is unclear. When quickly skimming over the buttons, the tooltips are not shown.	Any Chart → Click the double arrow toolbar	1	1	2	1.33
10	Case Study Enable Interactivity Feedback Missing	In Section 7, Step 6, there is no clear feedback from the application if interactivity is enabled or not.	Section 7 → Step 6 → Enable Interactivity	2	0	2	1.33
11	Download CSV Button Not Available in Chart Toolbar	In order to download a CSV file of the dataset, the user needs to view the data table. The Download CSV button should possibly be made available in the Toolbar.	Go to any chart → Toolbar → Table	2	0	1	1.00

Table 6.9: Aggregated list of all problems found, in descending order of average (mean) severity. Severity ratings were assigned by three project team members: KA, RG, and FZ (see Table 6.10).

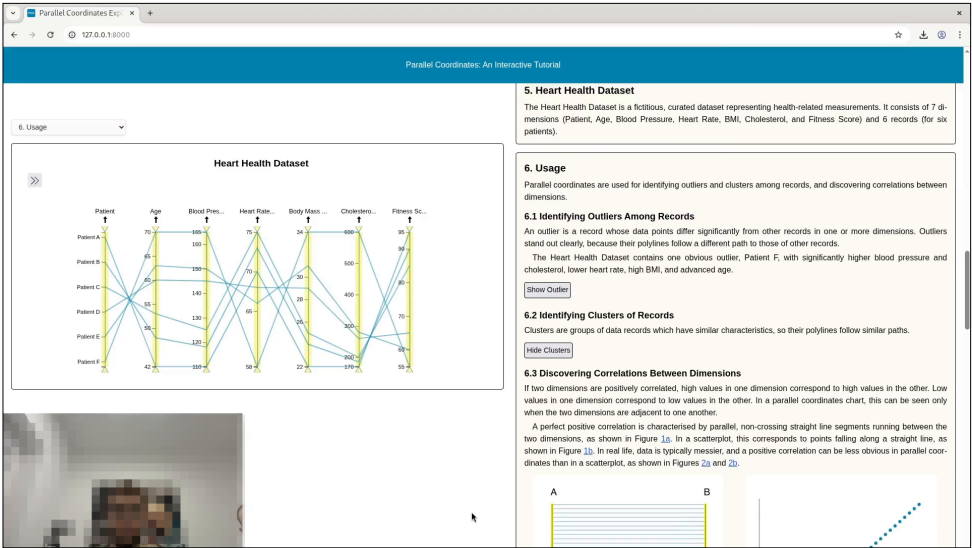


Figure 6.10: No explanation is provided for the case study.

Code	Meaning
KA	Keith Andrews
RG	Romana Gruber
FZ	Florian Zollner

Table 6.10: Name codes used for severity ratings.

6.4.6 Interviews

TP1 “Peter” immediately mentioned that he would have expected a filter icon and not an entry in the context menu. He loved the interactivity and wanted to directly access the chart in Section 7 without going to the last step. He understood what parallel coordinates are, but wondered about the meaning behind the name.

TP2 “Bob” pointed out that the “position” of the context menu is not intuitive, that he was confused at first that the chart in Section 7 only enabled interactivity in the last step and that it is difficult to catch a polyline. He liked the fact that he learned a new skill and mentioned that he might use parallel coordinates in his professional life.

TP3 “Julian” mentioned that the tool was interesting and the interactivity was nice. He now knows what parallel coordinates are and liked the “playful” experience. He found the data of the heart health dataset interesting, but was overwhelmed with the amount of data in the chart of Section 7. He was unhappy that 0 could not be entered in the first table.

TP4 “James” found it hard to distinguish individual polylines and was frustrated that he could not find the context menu. He found the parallel coordinates interesting and understands them better. He noted that the technique is not optimal for huge amounts of data. For the chart actions, he would have liked a separate menu for controlling actions like reversing. It was a pleasant experience for him, but he was irritated with the scrolling speed being too fast.

TP5 “Robert” found the experience fun, straightforward, and most of it well explained. He can use parallel coordinates now and liked the learning process. He does not like to work with a touchpad and found it hard to select polylines.

6.4.7 Feedback Questionnaires

Table 6.11 shows a summary of the ratings given by users in the feedback questionnaire at the end of the test. The neutral scale in the original feedback questionnaire has been mapped to a weighted scale between 6 (best) and 0 (worst). The numbers in bold indicate the (rounded) mean rating. The original blank questionnaire can be found in Appendix A.7. Scans of the questionnaires as completed by each test user can be found in Appendix B.2.

As can be seen in the ratings for Questions 11 and 12, the test users enjoyed working through PCEE, and successfully gained an understanding of the parallel coordinates technique. They also assessed the quality of the information in the tutorial to be quite high.

No.	Question	Left (best)	Scale	Right (worst)	TP1	TP2	TP3	TP4	TP5	Mean	SD
1	Getting to the right part of the site.	Very easy	6 5 4 3 2 1 0	Very hard	6	5	5	5	5	5.20	0.45
2	Quality of information.	Very good	6 5 4 3 2 1 0	Very poor	5	6	5	5	6	5.40	0.55
3	It is easy to read the text.	Very easy	6 5 4 3 2 1 0	Very hard	4	1	3	6	6	4.00	2.12
4	Appearance of site, including colours and graphics.	Very good	6 5 4 3 2 1 0	Very poor	5	4	2	1	5	3.40	1.82
5	Consistency of site.	Very consistent	6 5 4 3 2 1 0	Very inconsistent	3	6	6	5	6	5.20	1.30
6	Speed of pages displaying.	Very fast	6 5 4 3 2 1 0	Very slow	6	6	6	3	6	5.40	1.34
7	Overall impression of the web site.	Very good	6 5 4 3 2 1 0	Very bad	5	5	3	3	6	4.40	1.34
8	Do you consider this site to be trustworthy?	Definitely	6 5 4 3 2 1 0	Not at all	6	6	5	4	6	5.40	0.89
9	How likely are you to return to this site later?	Definitely	6 5 4 3 2 1 0	Never	4	4	0	1	0	1.80	2.05
10	Would you recommend this site to a friend or colleague?	Definitely	6 5 4 3 2 1 0	Never	4	5	5	4	6	4.80	0.84
11	Do you understand parallel coordinates after going through the explainer?	Very much	6 5 4 3 2 1 0	Not at all	5	6	6	5	6	5.60	0.55
12	Was it a pleasant experience going through the tutorial?	Definitely	6 5 4 3 2 1 0	Not at all	6	5	5	5	6	5.40	0.55

Table 6.11: Summary of user ratings from the feedback questionnaire (scale: 6 = best, 0 = worst).
The value in bold indicates the rounded mean rating.

Chapter 7

Concluding Remarks

This thesis evaluated the Parallel Coordinates Explorable Explainer (PCEE), an interactive tutorial in the style of an explorable explainer, which teaches parallel coordinates to new users. Two evaluation methods were applied: a heuristic evaluation (HE) by expert reviewers and a thinking aloud (TA) test with representative users. The HE is reported separately [Zollner 2025b]. This thesis presents the TA test.

7.1 Findings of the Thinking Aloud Test

Five test users from the user group “independent study” worked through the PCEE tutorial and then carried out five tasks. Each user finished the tutorial and recognised the correlation between Maths and IT in the case study. The tasks which required the chart toolbar and the context menu went less well, with the range task completed by three of five users and the image download by four (Section 6.4.1).

The tests produced three positive findings and eleven problems. The most positive finding, with a mean positivity of 3.67, was that hovering over a polyline shows its values on every dimension. The two most severe problems, both rated 3.00, were that the chart cannot be redrawn once a zero has been typed into the table in Section 2, and that a single polyline is hard to follow in the densely populated chart of Section 7.

The feedback questionnaire shows that PCEE meets its central aim. Understanding of parallel coordinates after working through the explainer was rated 5.60 out of 6, and the experience was rated 5.40 out of 6 (Section 6.4.7). One rating stands out against this. Asked how likely they were to return to the site, the users answered 1.80, the lowest of the twelve values in the questionnaire. The question asks about revisiting a web site, not about learning, so a low rating need not count against a tutorial which has already taught its topic.

7.2 Comparison with the Heuristic Evaluation

As discussed in Chapter 4, thinking aloud testing and heuristic evaluation are performed differently and produce similar but different results. It is often good practice to run both evaluation methods on the same application. In the case of PCEE, the heuristic evaluation with four expert evaluators produced 12 positive findings, 48 problems, and 7 bugs [Zollner 2025b]. The thinking aloud test with five test users produced 3 positive findings and 11 problems. Heuristic evaluation reported roughly four times as many problems. The difference on its own does not show which method came closer to the truth. The two studies also differ in reach, since the heuristic evaluation scanned the whole application, whereas the thinking aloud test followed six prescribed tasks.

Some problems were found by both methods, for example the difficulty in selecting a single polyline, and the missing explanation of the case study. Problems with inputting data into the table were flagged in both, although the experts entered characters and the users entered a zero.

One comparison documents an improvement. Not showing the values of a polyline on hover was the third most severe expert problem [Zollner 2025b]. In the TA test, the same interaction was the top-placed positive finding. The behaviour was added to PCEE between the two studies, and the users noticed it without being asked.

A final difference comes from the setting rather than from the software. The evaluators in the heuristic evaluation were provided with a mouse (and no touchpad). The users in the thinking aloud test used a laptop with a touchpad (and no mouse). Although actually an oversight in the test design, this circumstance did surface the issue of the touchpad being overly sensitive.

7.3 Contribution

The main contribution of this thesis is a documented, prioritised set of usability findings for PCEE, which rests on observed use rather than on expert judgement. Each problem has an associated reproduction path, severity rating, and video clip, so that the development team can act on it without repeating the study (Section 6.4.5). The video clips are available with the online version of the report [Zollner 2026]. Together with the HE, this gives PCEE two different views of its weaknesses.

7.4 Limitations

The study covered one of the two user profiles identified for PCEE. All five test users belonged to the group “independent study”, so the profile of students in an InfoVis class remains untested (Section 6.3.2). All five had no prior knowledge of parallel coordinates, which was a selection criterion rather than a coincidence.

The sample size follows the formative purpose of the study and is common for problem discovery, but it limits what the numbers mean. A problem seen by one user out of five cannot be told apart from a problem which is rare. The severity and positivity ratings in the TA were assigned by three members of the project team rather than by independent raters, so the evaluator effect described in Section 4.3 applies to the ratings as well as to the findings.

The comparison in Section 7.2 carries a further caveat. The two studies did not examine the same version of PCEE. The heuristic evaluation ran on the branches “Test-2025-09-24” and “Test-2025-09-30” in September and October 2025 [Zollner 2025b], whereas the thinking aloud test ran on the branch “Test-2025-12-03” in December 2025 (Section 6.2). Development continued between the two versions, and at least one change is visible in the results, namely the display of polyline values on hover. Where the two studies disagree, the cause may therefore lie in the method or in the software, and this study cannot separate the two.

Every session used the same laptop, browser, and screen size. PCEE is a web application which users will open on their own devices, and nothing in this study assesses how it behaves on a small screen or on a touch device.

7.5 Future Work

The untested user profile deserves a study of its own. PCEE was designed for a lecturer to introduce in class before students continue alone, and that path involves a different situation, a different starting point, and possibly different problems. A test with students in an InfoVis class would close that gap. One of

the problems found has since been addressed in the underlying library. SPCD3 gained a zoom mode in August 2026 [Andrews and Gruber 2026e]. Testing on smaller devices with touch screens is a second open point, and one which Andrews and Gruber [2025] already name as a challenge for PCEE. Beyond that, the low rating for returning to the site invites a question which this study cannot answer. It is unclear whether an explorable explainer goes unrevisited, because its readers can apply the technique on their own afterwards, or whether they would simply choose a different route back to the material when the need arises.

Appendix A

Project Team Materials

The following materials were prepared and used by the project team to conduct the Thinking Aloud (TA) tests described in Chapter 6.

A.1 Checklist

The checklist used for the TA tests is shown in Figure A.1.

A.2 Orientation Script

The orientation script used for the TA tests is shown in Figure A.2.

A.3 Consent Form

The blank consent form used in the TA tests is shown in Figure A.3.

A.4 Background Questionnaire

The blank background questionnaire used in the tests is shown in Figure A.4.

A.5 Task Slips

The task slips presented to the test users are shown in Figure A.5.

A.6 Interview Script

The interview script used in the tests is shown in Figure A.6.

A.7 Feedback Questionnaire

The blank feedback questionnaire used in the tests is shown in Figure A.7.

Checklist for Thinking Aloud Test

1. Preparation:

- ☐ Reset interface for new user.
- ☐ Check that everything is ready in test room.

2. Opening:

- ☐ Greet the participant.
- ☐ Go through orientation script and set the stage.
- ☐ Ask user to read and sign consent and non-disclosure forms.
- ☐ Background questionnaire: facilitator asks and fills out form.

3. Test Session:

- ☐ Move over to testing area (computer).
- ☐ Start session recording.
- ☐ Provide training of thinking aloud.
- ☐ User begins with tasks.
- ☐ User finishes last task.

4. Closing:

- ☐ Interview: how was it?
- ☐ Structured interview questions.
- ☐ Individual interview questions arising from test.
- ☐ Feedback questionnaire: user fills out form.
- ☐ Thank participant, provide any remuneration, show participant out.
- ☐ Stop session recording.

5. Wrap-Up:

- ☐ Summarise thoughts about this test.
- ☐ Organise data sheets and notes.
- ☐ Check and archive session recordings.

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Figure A.1: Checklist used for the Thinking Aloud tests. [Provided by Keith Andrews, used under the terms of a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.]

Orientation Script

Hi, my name is Florian. I'll be working with you in today's session. I am here to test a web application and would like your help.

I will ask you to perform some typical tasks with the web application. Do your best, but don't be overly concerned with results - the system is being tested, and not your performance. Since the system is not perfect, there will probably be some rough edges and bugs and things may not work exactly as you expect.

My only role here today is to discover the flaws and advantages of this system from your perspective. Don't act or say things based on what you think I might want to see or hear, I need to know what you really think.

So that I can better follow your trail of thoughts during the test, I will ask you to think aloud while you work. Please do ask questions at any time, but I may only answer them at the end of the session.

While you are working, I will be taking some notes. We will also be recording the session to create video clips of the findings.

If you feel uncomfortable, you may stop the test at any time.

Do you have any questions?

If not, then let's begin by filling out a short background questionnaire and having you sign the consent form.

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Figure A.2: Orientation script used for the Thinking Aloud tests. [Adapted from the original by Keith Andrews, used under the terms of a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.]

TID: _____
[of the form PCEE-2025-12-TID]

Declaration of Consent

The purpose of this evaluation is to examine the usability and utility of a web application from the perspective of novice users. The evaluation is being conducted by Florian Zollner, in Dec 2025, at Graz University of Technology, supervised by Prof. Keith Andrews (kandrews@tugraz.at). Your participation in this evaluation is voluntary.

Video recordings (screen, face, and audio) will be made of your session.

The sociodemographic, behavioural, and attitudinal data collected from your participation in this evaluation will be assigned an anonymous Test person ID (TID) of the form PCEE-2025-12-TID, and a first name alias. When reporting or sharing the data collected from this evaluation, only the TID or first name alias will be used when referring to your data. Short video clips will be extracted from the full video recordings to illustrate findings; in this case, faces will be blurred or pixelated appropriately.

You can withdraw your consent to the storage of your personal data (name, signature, and full video recordings) at any time by sending email to kandrews@tugraz.at quoting your TID. The withdrawal of consent does not affect the legality of the processing of data retrospectively.

By signing this Declaration of Consent, you affirm that you have read this declaration, you are aged 18 or over, the evaluation has been explained to you, your questions have been answered, and you agree to take part in this evaluation.

I freely consent to the processing of the data cited:

Participant (Print Name)

Place, Date

Signature

Data Protection Information

Controller:	Graz University of Technology, Rechbauerstraße 12, 8010 Graz. datenschutz@tugraz.at
Data Protection Officer:	x-tention Informationstechnologie GmbH, Römerstraße 80A, 4600 Wels. datenschutzbeauftragter@tugraz.at
Personal Data:	Name, signature, and full video recordings.
Purpose of Processing:	Documentation obligation (name and signature) and post-evaluation control (full video recordings).
Basis in Law:	Consent pursuant to GDPR Art 6 (1) (a).
Recipient:	No transmission to third parties; no contract processing.
Transmission to third countries:	No.
Duration of Storage:	One year, or sooner if consent is withdrawn.
Data Subject Rights:	You have the right to access, rectify, erase, restrict, object to, and delete your personal data. Besides these, you also have the right to withdraw your consent to the processing of your personal data. However, bear in mind that withdrawal of consent does not affect the legality of the processing of your data retrospectively. To exercise these rights please contact kandrews@tugraz.at . You also have a right to make a complaint to the Austrian Data Protection Authority at www.dsb.gv.at .

Figure A.3: Consent form used for the Thinking Aloud tests. [Adapted from the original by Keith Andrews, used under the terms of a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.]

Date: _____ Time: _____ Test User ID: _____

Background Questionnaire

1. General Information

Gender: ☐ *man* ☐ *woman* ☐ *non-binary* ☐ *prefer not to disclose*
 ☐ *prefer to self-describe, _____*

Age: _____

Occupation: _____

2. Education

1. What is the highest level of education you have attained?

☐ *vocational training* ☐ *secondary school* ☐ *university degree* ☐ *doctorate*

2. If you are studying or have studied, please describe your main area of study:

3. Personal Computer Use

1. Which kind of personal computer do you use most?

☐ *None* ☐ *Microsoft Windows* ☐ *Apple Macintosh* ☐ *Unix* ☐ *other _____*

2. How long have you been using a personal computer?

_____ *years*

3. How many hours per week do you use a personal computer?

_____ *hours*

4. Tablet Use

1. Which kind of tablet do you use most?

Figure A.4: Background questionnaire used for the Thinking Aloud tests. [Adapted from the original by Keith Andrews, used under the terms of a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.]

☐ None ☐ Android ☐ Apple (iOS) ☐ other _____

2. How long have you been using a tablet?

_____ *years*

3. How many hours per week do you use a tablet?

_____ *hours*

5. Smartphone Use

1. Which kind of smartphone do you use most?

☐ None ☐ Android ☐ Apple (iOS) ☐ other _____

2. How long have you been using a smartphone?

_____ *years*

3. How many hours per week do you use a smartphone?

_____ *hours*

6. Web Use

1. How many hours per week do you use the World Wide Web?

_____ *hours*

2. Which kind of device do you use most often to surf the web?

☐ desktop computer ☐ laptop ☐ tablet
☐ smartphone ☐ other _____

3. What kind of internet connection do you normally use?

☐ xDSL ☐ cable modem ☐ fibre optic
☐ 3G mobile internet ☐ 4G mobile internet ☐ other _____

4. Which web browser do you normally use?

☐ Chrome ☐ Firefox ☐ Safari ☐ Edge ☐ other _____

5. Do you have experience as a web site administrator?

Figure A.4: Background questionnaire used for the Thinking Aloud tests (Continued).

If yes: _____ years

7. Domain-Specific Questions

1. Do you know what parallel coordinates are?

[] yes, explain _____

[] no

2. Have you used any interactive tools for analysing multidimensional (spreadsheet) data?

[] yes, which _____

[] no

3. Do you have experience using interactive tutorials?

[] yes

[] no

8. Experience with Usability Tests

1. Have you participated in a usability study before?

[] as a test user

[] as part of the test team

If yes, what kind of study was it?

[] Thinking Aloud

[] Formal Experiment

[] other _____

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Figure A.4: Background questionnaire used for the Thinking Aloud tests (Continued).

Please go to the web site:
<https://tugraz-isds.github.io/pcee/>
and work your way through the tutorial about Parallel Coordinates.

Go to Section 7 Case Study: Student Marks
In the final step (Step 6), enable interactivity, so
you can explore the dataset.
Do some analysis to check whether there may be a correlation
between student marks in Maths and IT.

Go to Section 2 Personal Finances Dataset
Add some extra data to the dataset using the table
and see how that affects the chart.

Go to Section 2 Personal Finances Dataset
Let the range of the Income and Cost Column start at 0

Go to Section 2 Personal Finances Dataset
Download an image of the chart

Go to Section 5 Heart Health Dataset
Download the table as a CSV file to work with it in Excel.

Figure A.5: Task slips used for the Thinking Aloud tests. [Adapted from the template provided by Keith Andrews, used under the terms of a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.]

Interview Script

1 Opening Question

- “How was it?”

[Let the user speak, and encourage them, until they dry up and stop of their own accord.]

2 Standard Questions

1. “Did anything strike you as particularly good?”
2. “Did anything strike you as particularly bad?”
3. "Do you know what parallel coordinates are after going through the tutorial?"

3 Individual Questions

At this point, ask any questions which arose during the test with each particular test user.

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Figure A.6: Interview script used for the Thinking Aloud tests. [Adapted from the template provided by Keith Andrews, used under the terms of a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.]

Date: _____ Time: _____ Test User ID: _____

Feedback Questionnaire

Please rate your satisfaction with these aspects of the web site you have just finished working with, by circling the most appropriate number.

1. Getting to the right part of the site.	Very easy	3	2	1	0	1	2	3	Very hard
2. Quality of information.	Very good	3	2	1	0	1	2	3	Very poor
3. It is easy to read the text.	Very easy	3	2	1	0	1	2	3	Very hard
4. Appearance of site, including colours and graphics.	Very good	3	2	1	0	1	2	3	Very poor
5. Consistency of site.	Very consistent	3	2	1	0	1	2	3	Very inconsistent
6. Speed of pages displaying.	Very fast	3	2	1	0	1	2	3	Very slow
7. Overall impression of the web site.	Very good	3	2	1	0	1	2	3	Very bad
8. Do you consider this site to be trustworthy?	Definitely	3	2	1	0	1	2	3	Not at all
9. How likely are you to return to this site later?	Definitely	3	2	1	0	1	2	3	Never
10. Would you recommend this site to a friend or colleague?	Definitely	3	2	1	0	1	2	3	Never
11. Do you understand parallel coordinates after going through the explainer?	Very much	3	2	1	0	1	2	3	Not at all
12. Was it a pleasant experience going through the tutorial?	Definitely	3	2	1	0	1	2	3	Not at all

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Figure A.7: Feedback questionnaire used for the Thinking Aloud tests. [Adapted from the template provided by Keith Andrews, used under the terms of a Creative Commons Attribution 4.0 International (CC BY 4.0) licence.]

Appendix B

User Materials

The following materials were filled out for each test user during the TA tests described in Chapter 6.

B.1 Completed Background Questionnaires

The completed background questionnaires for test users TP1 “Peter” through TP5 “Robert” are shown in Figures B.1 to B.5.

B.2 Completed Feedback Questionnaires

The completed feedback questionnaires for test users TP1 “Peter” through TP5 “Robert” are shown in Figures B.6 to B.10.

Date: 03.12.2025 Time: 10:00 Test User ID: PCEE-2025-12-T1

Background Questionnaire

1. General Information

Gender: ☒ man ☐ woman ☐ non-binary ☐ prefer not to disclose

☐ prefer to self-describe, _____

Age: 23

Occupation: Magisters at TU Graz

2. Education

1. What is the highest level of education you have attained?

☐ vocational training ☐ secondary school ☒ university degree ^{BSc} ☐ doctorate

2. If you are studying or have studied, please describe your main area of study:

Information Sec

3. Personal Computer Use

1. Which kind of personal computer do you use most?

☐ None ☐ Microsoft Windows ☐ Apple Macintosh ☒ Unix ^{Linux} ☐ other _____

2. How long have you been using a personal computer?

12 years

3. How many hours per week do you use a personal computer?

60 hours

4. Tablet Use

1. Which kind of tablet do you use most?

☒ None ☐ Android ☐ Apple (iOS) ☐ other _____

Figure B.1: Background questionnaire completed by test user TP1 “Peter”.

2. How long have you been using a tablet?

_____ years

3. How many hours per week do you use a tablet?

_____ hours

5. Smartphone Use

1. Which kind of smartphone do you use most?

☐ None ☒ Android ☐ Apple (iOS) ☐ other _____

2. How long have you been using a smartphone?

12 years

3. How many hours per week do you use a smartphone?

10 hours

6. Web Use

1. How many hours per week do you use the World Wide Web?

20 hours

2. Which kind of device do you use most often to surf the web?

☐ desktop computer ☒ laptop ☐ tablet
☐ smartphone ☐ other _____

3. What kind of internet connection do you normally use?

☐ xDSL ☒ cable modem ☐ fibre optic
☐ 3G mobile internet ☐ 4G mobile internet ☐ other _____

4. Which web browser do you normally use?

☐ Chrome ☒ Firefox ☐ Safari ☐ Edge ☐ other _____

5. Do you have experience as a web site administrator?

If yes: 2 years

7. Domain-Specific Questions

Figure B.1: Background questionnaire completed by test user TP1 “Peter” (Continued).

1. Do you know what parallel coordinates are?

☐ yes, explain _____ ☒ no

2. Have you used any interactive tools for analysing multidimensional (spreadsheet) data?

☒ yes, which Excel ☐ no

3. Do you have experience using interactive tutorials?

☒ yes ☐ no

8. Experience with Usability Tests

1. Have you participated in a usability study before?

☒ as a test user ☒ as part of the test team

If yes, what kind of study was it?

☒ Thinking Aloud ☐ Formal Experiment ☐ other _____

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Figure B.1: Background questionnaire completed by test user TP1 “Peter” (Continued).

FREE-2021-12-T2

Date: 04.12.2025 Time: 20:15 Test User ID: 02

Background Questionnaire

1. General Information

Gender: ☒ man ☐ woman ☐ non-binary ☐ prefer not to disclose
☐ prefer to self-describe, _____

Age: 32

Occupation: Software Engineer / Sales

2. Education

1. What is the highest level of education you have attained?
☐ vocational training ☐ secondary school ☒ ^{MSc} university degree ☐ doctorate

2. If you are studying or have studied, please describe your main area of study:
Mechanical Eng & Comp. Scien

3. Personal Computer Use

1. Which kind of personal computer do you use most?
☐ None ☒ Microsoft Windows ☐ Apple Macintosh ☐ Unix ☐ other _____

2. How long have you been using a personal computer?
25 years

3. How many hours per week do you use a personal computer?
50 hours

4. Tablet Use

1. Which kind of tablet do you use most?
☒ None ☐ Android ☐ Apple (iOS) ☐ other _____

Figure B.2: Background questionnaire completed by test user TP2 “Bob”.

2. How long have you been using a tablet?

_____ years

3. How many hours per week do you use a tablet?

_____ hours

5. Smartphone Use

1. Which kind of smartphone do you use most?

☐ None ☒ Android ☐ Apple (iOS) ☐ other _____

2. How long have you been using a smartphone?

15 years

3. How many hours per week do you use a smartphone?

7 hours 1h/Day

6. Web Use

1. How many hours per week do you use the World Wide Web?

37 hours 57

2. Which kind of device do you use most often to surf the web?

☐ desktop computer ☒ laptop ☐ tablet
☐ smartphone ☐ other _____

3. What kind of internet connection do you normally use?

☐ xDSL ☐ cable modem ☒ fibre optic
☐ 3G mobile internet ☐ 4G mobile internet ☐ other _____

4. Which web browser do you normally use?

☐ Chrome ☒ Firefox ☐ Safari ☐ Edge ☐ other _____

5. Do you have experience as a web site administrator?

If yes: _____ years

7. Domain-Specific Questions

Figure B.2: Background questionnaire completed by test user TP2 “Bob” (Continued).

1. Do you know what parallel coordinates are?

☐ yes, explain _____ ☒ no

2. Have you used any interactive tools for analysing multidimensional (spreadsheet) data?

☒ yes, which NumPy/Excel ☐ no

3. Do you have experience using interactive tutorials?

☒ yes ☐ no

8. Experience with Usability Tests

1. Have you participated in a usability study before?

☐ as a test user ☐ as part of the test team ☒ no

If yes, what kind of study was it?

☐ Thinking Aloud ☐ Formal Experiment ☐ other _____

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Figure B.2: Background questionnaire completed by test user TP2 “Bob” (Continued).

Date: 05.12.2025 Time: 17:45 Test User ID: PCEE-2025-12-T 3

Background Questionnaire

1. General Information

Gender: ☒ man ☐ woman ☐ non-binary ☐ prefer not to disclose

☐ prefer to self-describe, _____

Age: 20

Occupation: Self Employed Finance

2. Education

1. What is the highest level of education you have attained?

☐ vocational training ☐ secondary school ☐ university degree ☐ doctorate Aliter

2. If you are studying or have studied, please describe your main area of study:

3. Personal Computer Use

1. Which kind of personal computer do you use most?

☐ None ☒ Microsoft Windows ☐ Apple Macintosh ☐ Unix ☐ other _____

2. How long have you been using a personal computer?

5-6 years

3. How many hours per week do you use a personal computer?

56 hours 7-24h/Day

4. Tablet Use

1. Which kind of tablet do you use most?

☒ None ☐ Android ☐ Apple (iOS) ☐ other _____

Figure B.3: Background questionnaire completed by test user TP3 “Julian”.

2. How long have you been using a tablet?

_____ years

3. How many hours per week do you use a tablet?

_____ hours

5. Smartphone Use

1. Which kind of smartphone do you use most?

☐ None ☒ Android ☐ Apple (iOS) ☐ other _____

2. How long have you been using a smartphone?

8-7 years

3. How many hours per week do you use a smartphone?

35 hours 5 / Day

6. Web Use

1. How many hours per week do you use the World Wide Web?

35 hours 5 / Day

2. Which kind of device do you use most often to surf the web?

☐ desktop computer ☐ laptop ☐ tablet
☒ smartphone ☐ other _____

3. What kind of internet connection do you normally use?

☐ xDSL ☐ cable modem ☐ fibre optic
☐ 3G mobile internet ☐ 4G mobile internet ☒ other 5G

4. Which web browser do you normally use?

☒ Chrome ☐ Firefox ☐ Safari ☐ Edge ☐ other _____

5. Do you have experience as a web site administrator?

If yes: _____ years

7. Domain-Specific Questions

Figure B.3: Background questionnaire completed by test user TP3 “Julian” (Continued).

1. Do you know what parallel coordinates are?

☐ yes, explain _____ ☒ no

2. Have you used any interactive tools for analysing multidimensional (spreadsheet) data?

☒ yes, which Excel ☐ no

3. Do you have experience using interactive tutorials?

☐ yes ☒ no ☐

8. Experience with Usability Tests

1. Have you participated in a usability study before?

☐ as a test user ☐ as part of the test team ☒ No

If yes, what kind of study was it?

☐ Thinking Aloud ☐ Formal Experiment ☐ other _____

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Figure B.3: Background questionnaire completed by test user TP3 “Julian” (Continued).

Date: 06.12.2025 Time: 15:00 Test User ID: PLEE-2025-12-T 4

Background Questionnaire

1. General Information

Gender: ☒ man ☐ woman ☐ non-binary ☐ prefer not to disclose

☐ prefer to self-describe, _____

Age: 23

Occupation: Wealth Consultant

2. Education

1. What is the highest level of education you have attained?

☐ vocational training ☐ secondary school ☐ university degree ☐ doctorate

2. If you are studying or have studied, please describe your main area of study:

Physics

3. Personal Computer Use

1. Which kind of personal computer do you use most?

☐ None ☐ Microsoft Windows ☒ Apple Macintosh ☐ Unix ☐ other _____

2. How long have you been using a personal computer?

15 years

3. How many hours per week do you use a personal computer?

56 hours

4. Tablet Use

1. Which kind of tablet do you use most?

☐ None ☐ Android ☒ Apple (iOS) ☐ other _____

Figure B.4: Background questionnaire completed by test user TP4 “James”.

2. How long have you been using a tablet?

6-7 years

3. How many hours per week do you use a tablet?

14 hours

5. Smartphone Use

1. Which kind of smartphone do you use most?

☐ None ☐ Android ☒ Apple (iOS) ☐ other _____

2. How long have you been using a smartphone?

10 years

3. How many hours per week do you use a smartphone?

14 hours

6. Web Use

1. How many hours per week do you use the World Wide Web?

56 hours

2. Which kind of device do you use most often to surf the web?

☐ desktop computer ☒ laptop ☐ tablet
☐ smartphone ☐ other _____

3. What kind of internet connection do you normally use?

☐ xDSL ☐ cable modem ☐ fibre optic
☐ 3G mobile internet ☐ 4G mobile internet ☒ other 5G

4. Which web browser do you normally use?

☐ Chrome ☐ Firefox ☒ Safari ☐ Edge ☐ other _____

5. Do you have experience as a web site administrator?

If yes: _____ years

7. Domain-Specific Questions

Figure B.4: Background questionnaire completed by test user TP4 “James” (Continued).

1. Do you know what parallel coordinates are?

☐ yes, explain _____ ☒ no

2. Have you used any interactive tools for analysing multidimensional (spreadsheet) data?

☒ yes, which Excel ☐ no

3. Do you have experience using interactive tutorials?

☒ yes ☐ no

8. Experience with Usability Tests

1. Have you participated in a usability study before?

☐ as a test user ☐ as part of the test team ☒ No

If yes, what kind of study was it?

☐ Thinking Aloud ☐ Formal Experiment ☐ other _____

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Figure B.4: Background questionnaire completed by test user TP4 “James” (Continued).

Date: 07.12.2025 Time: 14:10 Test User ID: PLG-2025-12-T5

Background Questionnaire

1. General Information

Gender: ☒ man ☐ woman ☐ non-binary ☐ prefer not to disclose

☐ prefer to self-describe, _____

Age: 24

Occupation: TU Vienna

2. Education

1. What is the highest level of education you have attained?

☐ vocational training ☒ secondary school ☐ university degree ☐ doctorate

2. If you are studying or have studied, please describe your main area of study:

Physics

3. Personal Computer Use

1. Which kind of personal computer do you use most?

☐ None ☐ Microsoft Windows ☐ Apple Macintosh ☒ Unix ☐ other _____

2. How long have you been using a personal computer?

11 years

3. How many hours per week do you use a personal computer?

7 hours

4. Tablet Use

1. Which kind of tablet do you use most?

☐ None ☐ Android ☒ Apple (iOS) ☐ other _____

Figure B.5: Background questionnaire completed by test user TP5 “Robert”.

2. How long have you been using a tablet?

3 years

3. How many hours per week do you use a tablet?

35 hours

5. Smartphone Use

1. Which kind of smartphone do you use most?

☐ None ☒ Android ☐ Apple (iOS) ☐ other _____

2. How long have you been using a smartphone?

12-13 years

3. How many hours per week do you use a smartphone?

10,5 hours 1,5 h / Day

6. Web Use

1. How many hours per week do you use the World Wide Web?

28 hours 4 h / Day

2. Which kind of device do you use most often to surf the web?

☐ desktop computer ☐ laptop ☒ tablet
☐ smartphone ☐ other _____

3. What kind of internet connection do you normally use?

☐ xDSL ☐ cable modem ☒ fibre optic
☐ 3G mobile internet ☐ 4G mobile internet ☐ other _____

4. Which web browser do you normally use?

☐ Chrome ☒ Firefox ☐ Safari ☐ Edge ☐ other _____

5. Do you have experience as a web site administrator?

If yes: _____ years

7. Domain-Specific Questions

Figure B.5: Background questionnaire completed by test user TP5 “Robert” (Continued).

1. Do you know what parallel coordinates are?

☐ yes, explain _____ ☒ no

2. Have you used any interactive tools for analysing multidimensional (spreadsheet) data?

☒ yes, which Excel ☐ no

3. Do you have experience using interactive tutorials?

☐ yes ☒ no

8. Experience with Usability Tests

1. Have you participated in a usability study before?

☐ as a test user ☐ as part of the test team ☒ No

If yes, what kind of study was it?

☐ Thinking Aloud ☐ Formal Experiment ☐ other _____

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Figure B.5: Background questionnaire completed by test user TP5 “Robert” (Continued).

Date: 03.12.2025Time: 10:45Test User ID: PCEE-2025-12-T 1

Feedback Questionnaire

Please rate your satisfaction with these aspects of the web site you have just finished working with, by circling the most appropriate number.

1. Getting to the right part of the site.	Very easy	3	2	1	0	1	2	3	Very hard
2. Quality of information.	Very good	3	2	1	0	1	2	3	Very poor
3. It is easy to read the text.	Very easy	3	2	1	0	1	2	3	Very hard
4. Appearance of site, including colours and graphics.	Very good	3	2	1	0	1	2	3	Very poor
5. Consistency of site.	Very consistent	3	2	1	0	1	2	3	Very inconsistent
6. Speed of pages displaying.	Very fast	3	2	1	0	1	2	3	Very slow
7. Overall impression of the web site.	Very good	3	2	1	0	1	2	3	Very bad
8. Do you consider this site to be trustworthy?	Definitely	3	2	1	0	1	2	3	Not all all
9. How likely are you to return to this site later?	Definitely	3	2	1	0	1	2	3	Never
10. Would you recommend this site to a friend or colleague?	Definitely	3	2	1	0	1	2	3	Never
11. Do you understand parallel coordinates after going through the explainer?	Very much	3	2	1	0	1	2	3	Not at all
12. Was it a pleasant experience going through the tutorial?	Definitely	3	2	1	0	1	2	3	Not at all

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Figure B.6: Feedback questionnaire completed by test user TP1 “Peter”.

PCEE-2025-12 T2

Date: 04.12.2025 Time: 21:00 Test User ID: 02

Feedback Questionnaire

Please rate your satisfaction with these aspects of the web site you have just finished working with, by circling the most appropriate number.

- | | |
|---|---|
| 1. Getting to the right part of the site. | Very easy 3 (2) 1 0 1 2 3 Very hard |
| 2. Quality of information. | Very good (3) 2 1 0 1 2 3 Very poor |
| 3. It is easy to read the text. | Very easy 3 2 1 0 1 (2) 3 Very hard |
| 4. Appearance of site, including colours and graphics. | Very good 3 2 (1) 0 1 2 3 Very poor |
| 5. Consistency of site. | Very consistent (3) 2 1 0 1 2 3 Very inconsistent |
| 6. Speed of pages displaying. | Very fast (3) 2 1 0 1 2 3 Very slow |
| 7. Overall impression of the web site. | Very good 3 (2) 1 0 1 2 3 Very bad |
| 8. Do you consider this site to be trustworthy? | Definitely (3) 2 1 0 1 2 3 Not all all |
| 9. How likely are you to return to this site later? | Definitely 3 2 (1) 0 1 2 3 Never |
| 10. Would you recommend this site to a friend or colleague? | Definitely 3 (2) 1 0 1 2 3 Never |
| 11. Do you understand parallel coordinates after going through the explainer? | Very much (3) 2 1 0 1 2 3 Not at all |
| 12. Was it a pleasant experience going through the tutorial? | Definitely 3 (2) 1 0 1 2 3 Not at all |

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Figure B.7: Feedback questionnaire completed by test user TP2 “Bob”.

PLCEP-2025-12 T3

Date: 5.12.2025 Time: 18:15 Test User ID: 03

Feedback Questionnaire

Please rate your satisfaction with these aspects of the web site you have just finished working with, by circling the most appropriate number.

1. Getting to the right part of the site.	Very easy	3	(2)	1	0	1	2	3	Very hard
2. Quality of information.	Very good	3	(2)	1	0	1	2	3	Very poor
3. It is easy to read the text.	Very easy	3	2	1	(0)	1	2	3	Very hard
4. Appearance of site, including colours and graphics.	Very good	3	2	1	0	(1)	2	3	Very poor
5. Consistency of site.	Very consistent	(3)	2	1	0	1	2	3	Very inconsistent
6. Speed of pages displaying.	Very fast	(3)	2	1	0	1	2	3	Very slow
7. Overall impression of the web site.	Very good	3	2	(1)	(0)	1	2	3	Very bad
8. Do you consider this site to be trustworthy?	Definitely	3	(2)	1	0	1	2	3	Not at all
9. How likely are you to return to this site later?	Definitely	3	2	1	0	1	2	(3)	Never
10. Would you recommend this site to a friend or colleague?	Definitely	(3)	(2)	1	0	1	2	3	Never
11. Do you understand parallel coordinates after going through the explainer?	Very much	(3)	2	1	0	1	2	3	Not at all
12. Was it a pleasant experience going through the tutorial?	Definitely	3	(2)	1	0	1	2	3	Not at all

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Figure B.8: Feedback questionnaire completed by test user TP3 “Julian”.

Date: 06.12.2025 Time: 15:30 Test User ID: PCEE-2025-12-T 4

Feedback Questionnaire

Please rate your satisfaction with these aspects of the web site you have just finished working with, by circling the most appropriate number.

- | | | | | | | | | | |
|---|-----------------|-----|-----|-----|-----|---|-----|---|-------------------|
| 1. Getting to the right part of the site. | Very easy | 3 | (2) | 1 | 0 | 1 | 2 | 3 | Very hard |
| 2. Quality of information. | Very good | 3 | (2) | 1 | 0 | 1 | 2 | 3 | Very poor |
| 3. It is easy to read the text. | Very easy | (3) | 2 | 1 | 0 | 1 | 2 | 3 | Very hard |
| 4. Appearance of site, including colours and graphics. | Very good | 3 | 2 | 1 | 0 | 1 | (2) | 3 | Very poor |
| 5. Consistency of site. | Very consistent | 3 | (2) | 1 | 0 | 1 | 2 | 3 | Very inconsistent |
| 6. Speed of pages displaying. | Very fast | 3 | 2 | 1 | (0) | 1 | 2 | 3 | Very slow |
| 7. Overall impression of the web site. | Very good | 3 | 2 | 1 | (0) | 1 | 2 | 3 | Very bad |
| 8. Do you consider this site to be trustworthy? | Definitely | 3 | 2 | (1) | 0 | 1 | 2 | 3 | Not at all |
| 9. How likely are you to return to this site later? | Definitely | 3 | 2 | 1 | 0 | 1 | (2) | 3 | Never |
| 10. Would you recommend this site to a friend or colleague? | Definitely | 3 | 2 | (1) | 0 | 1 | 2 | 3 | Never |
| 11. Do you understand parallel coordinates after going through the explainer? | Very much | 3 | (2) | 1 | 0 | 1 | 2 | 3 | Not at all |
| 12. Was it a pleasant experience going through the tutorial? | Definitely | 3 | (2) | 1 | 0 | 1 | 2 | 3 | Not at all |

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Figure B.9: Feedback questionnaire completed by test user TP4 “James”.

Date: 07.11.2025Time: 14:40Test User ID: PCEE-2025-12-T 5

Feedback Questionnaire

Please rate your satisfaction with these aspects of the web site you have just finished working with, by circling the most appropriate number.

1. Getting to the right part of the site.	Very easy 3 2 1 0 1 2 3 Very hard
2. Quality of information.	Very good 3 2 1 0 1 2 3 Very poor
3. It is easy to read the text.	Very easy 3 2 1 0 1 2 3 Very hard
4. Appearance of site, including colours and graphics.	Very good 3 2 1 0 1 2 3 Very poor
5. Consistency of site.	Very consistent 3 2 1 0 1 2 3 Very inconsistent
6. Speed of pages displaying.	Very fast 3 2 1 0 1 2 3 Very slow
7. Overall impression of the web site.	Very good 3 2 1 0 1 2 3 Very bad
8. Do you consider this site to be trustworthy?	Definitely 3 2 1 0 1 2 3 Not at all
9. How likely are you to return to this site later?	Definitely 3 2 1 0 1 2 3 Never
10. Would you recommend this site to a friend or colleague?	Definitely 3 2 1 0 1 2 3 Never
11. Do you understand parallel coordinates after going through the explainer?	Very much 3 2 1 0 1 2 3 Not at all
12. Was it a pleasant experience going through the tutorial?	Definitely 3 2 1 0 1 2 3 Not at all

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Figure B.10: Feedback questionnaire completed by test user TP5 “Robert”.

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