Custom Formula-Based Visualizations for Savvy Designers

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Abstract

Despite their usefulness in many domains (e.g. healthcare, finance, etc.), custom visualizations remain tedious and hard to implement. It would be advantageous if savvy designers (designers with basic programming knowledge and much domain knowledge) could refine visualizations to their needs. For instance, it would save time and money if a clinician familiar with spreadsheet formulas could refine a visualization (e.g. the lifelines) rather than hiring a programmer.

Existing approaches to visualization are one of the two: accessible to savvy designers but limited in customizability, or inaccessible and expressive. For instance, chart tools are easy to use, but support only predefined visualizations, while visualization tools support custom visualizations, but require program-like specifications.

This thesis presents Uvis, a visualization system that targets savvy designers. With Uvis, designers drag and drop visual objects, set the visual object properties with formulas, and see the result immediately. The formulas are declarative and similar to spreadsheet formulas. The formulas compute the property values and can refer to fields, visual properties, functions, etc.

This thesis hypothesizes that it is possible to express custom visualizations with spreadsheet-like formulas, and savvy designers can learn to refine the visualizations. The thesis presents four contributions: The first is the expressive power of formulas, substantiated with a collection of custom visualizations. The second contribution is iteratively refining Uvis based on feedback from savvy designers. Uvis provides novel cognitive aids that assist the designers in creating and refining custom visualizations. The third contribution is a usability evaluation of Uvis with savvy designers. The

fourth contribution is a usability analysis of several visualization tools including Uvis. The analysis highlights the differences between approaches and argues why Uvis is more suited for custom visualizations.

Apart from the thesis, I am the main author of two peer-reviewed, accepted papers and a co-author of another one.

Dedication

I dedicate this thesis to my beloved parents, wife, and family members.

I also dedicate it to all positive people in the world who always focus on changing themselves to the better and making the world a better place rather than blaming others, the situation, etc.

I also dedicate it to the children who are having a hard time. I hope the future will bring something positive to them. One by one, we all make a difference.

Acknowledgements

I would like to acknowledge my supervisor Soren Lauesen for helping me so much during my PhD studies. I have learned so much from him not only at a professional or academic level, but also a personal level.

Soren Lauesen invented the basic Uvis principles, including the formula principles. The rest of the initial Uvis ideas are the joint intellectual work of Mohammad Amin Kuhail, Soren Lauesen, Kostas Pantazos, and Shangjin XU (in alphabetical sequence). Each team member developed his version of Uvis to validate his research ideas.

I would like to acknowledge my parents and other family members who gave me a lot of positive energy during my PhD journey.

I would like to acknowledge my wife, Zara Al-Ali, who supported me during writing the thesis. She contributed so much to my success.

I would like to thank professor Margaret-Anne (Peggy) Storey who supervised me during my stay abroad in the CHISEL lab, Victoria, Canada. In general, all the lab members were friendly and inspiring.

I would like to acknowledge many of colleagues who inspired me with their innovative ideas and hard work. In particular, I would like to thank Kostas Pantazos, XU Shangjin, Soren Lippert, and Lars Grammel.

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Introduction

Information visualization (InfoVis) seeks to leverage human visual abilities to derive insights by showing data as position, colour, orientation, etc. The insights of InfoVis are applied in many areas such as financial data analysis, health care, biology, etc.

Despite the potential of InfoVis, implementing or refining custom visualizations such as Lifelines (3) remains time consuming and accessible only to experienced programmers.

Custom visualizations use position, size, shape, colour, and orientation to show data. However, unlike conventional visualizations (e.g. bar chart), they cannot be created by selecting predefined visualization templates and mapping data to the templates. Custom visualizations are tailored to a specific need, and designers might not be exactly sure about what the desired visualization should look like. It is a trial and error approach.

It would be advantageous if a *savvy designer*, a designer with basic programming skills and domain knowledge, could implement or refine a custom visualization. For instance, it would save a lot if clinicians with basic programming skills and domain knowledge were able to refine a lifelines visualization to their own needs rather than hiring a programmer to do it.

Allowing savvy designers to implement or refine custom visualizations necessitates an approach that combines ease of use and expressiveness.

There are many tools that support the creation of visualizations. The strengths and weaknesses of these tools can be summarized as follows:

- **Charting tools** such as Excel allow designers to create visualizations that correspond to predefined templates. Limited customization is possible. For instance, designers can change some appearance properties such as colour, text formatting, etc.

  This approach is accessible to savvy designers but does not support custom visualizations. Designers do not have full control over the fine building blocks of the visualization. For instance, not all the visual properties (e.g. `Height`) of the visual objects (e.g. ellipse, bar) are exposed. Moreover, designers cannot reuse the building blocks in other visualizations.

- **Analytical and exploratory tools** such as Spotfire (4) allow more data exploration than charting tools. They provide more visualization templates and functionalities.

  These tools are accessible to savvy designers and more expressive than charting tools. However, the designer's control over the resulting visualization is still limited, making the tools unsuited for the design of custom visualizations. For instance, a visualization like the Lifelines (3) can not be made.

- **Visualization tools** such as Prefuse (5) and Protovis (6) allow designers to build custom visualizations. The approaches of these tools vary from imperative to declarative programming. However, designers may still need to implement program-like specifications. For instance, designers need to declare variables, program functions, etc. Consequently, the gap between the objective (what the designer wants to accomplish) and the solution (how the designer accomplishes the objective) remains high. This is described by Norman as the gulf of execution (7).

- **Programming languages** provide graphics APIs such as GDI+ (8) and Java 2D (9) that can be used to create advanced visualizations, but these languages mainly target experienced programmers.

  The programming languages can be integrated with *development environments* (e.g. MS Visual Studio (10)). The environments allow programmers to manually build a non-functional user interface. The environments use the *drag-drop-set-property* approach. Programmers manually drag and drop graphical components

(buttons, text boxes, etc.) and set their properties. Then the screen looks right, but it has little functionality. Programming behind is needed to make the interface functional.

To sum up, existing tools are either inflexible and accessible to non-programmers, or flexible and inaccessible to non-programmers.

An evaluation study (11) found out that *drag-drop-set-property* tools (called interface builders and interactive graphical tools) were much more successful with designers than program-based tools. The study also reports that spreadsheets are the only kind of "programming" widely accepted by end-users.

MS Access is an example of a successful drag-drop-set-property tool. Designers create useful database applications by dragging and dropping UI elements (e.g. TextBox). Further, designers define formulas that make the elements show data. However, the formulas are very limited. For instance, it is not possible to show data as position, orientation, etc.

Inspired by MS Access, Uvis is a drag-drop-set-property tool where designers drag and drop visual objects, and specify formulas for the visual object properties. A formula computes and sets the value of a property, and can bind visual objects to data. A formula corresponds to a spreadsheet formula, but is able to combine data from databases, visual components and end-user input.

The following section explains the Uvis approach.

1.1 The Uvis Approach

The Uvis approach relies on these elements:

- The **development environment** assists the designer in creating or refining a visualization (Figure 1.1). The environment consists of seven panels: toolbox, visualization form, property grid, data model, error list, table view, and inspector. The *toolbox* is a list of the available visual objects. The *visualization form* contains the visualization the designer is currently building. The *property grid* allows the designer to change the properties (e.g. colour, position, etc.) of a visual object. The *error list* lists the problems in the visualization. The *data model* shows the structure of the data the designer wants to show. The *table view* shows a sample

1. INTRODUCTION

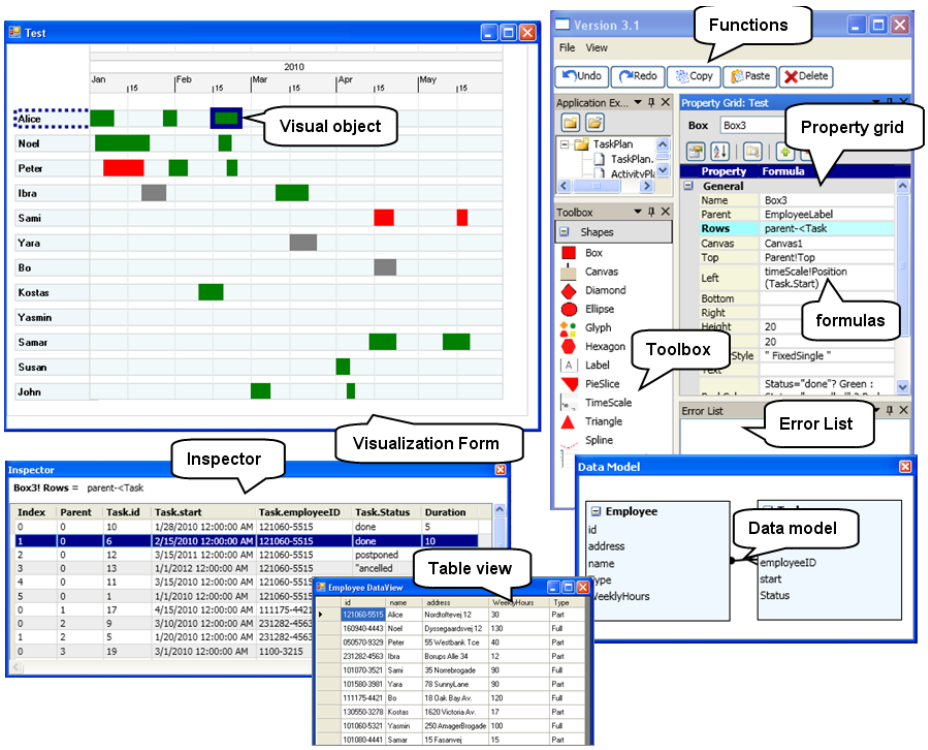


Figure 1.1: The Uvis environment

of the data in the data model. The *inspector* allows the designer to view data behind the visual objects and their properties.

- The **visual objects** are the building blocks of a visualization. They can be traditional UI elements (e.g. button, textbox), geometric shapes (e.g. ellipse, triangle), or specialized objects (e.g. time scale). The visual objects have properties that define their appearance (e.g. position, size, colour) and behaviour.

- **Formulas** are declarative spreadsheet-like expressions that can bind visual objects to data and make their properties represent the data. The formulas can refer to data fields, visual properties, functions, etc.

- The **documentation** is a tutorial that walks the designer step-wise through the main Uvis concepts. It is easy to read, and contains concrete examples.

To create a visualization, the designer drags a visual object from the toolbox and drops it on the visualization form. To make the visual object show data in the database, the designer sets the `Rows` property with an SQL-like formula that can retrieve a subset of tables in a relational database . The result is a local record set. Uvis creates a visual object for each row in the record set. Uvis automatically positions the visual objects like a staircase to make them visible to the designer. The designer sees the result immediately in the visualization form.

To make the properties of the visual objects show data, the designer can set the appearance properties (e.g. Height, Top) with formulas that refer to data fields in the record set. Again, the designer sees the impact of the formulas in the visualization form immediately.

If Uvis encounters errors while the designer is typing the formulas, Uvis highlights the problematic parts, and produces a list of the errors.

To check that the visual objects show the right data in the right way, the designer can select a visual object and view the data row behind it in the inspector. Moreover, the designer can inspect the values of the formula sub-expressions.

Now we will give an example of how to create a visualization with Uvis. The example uses the same style used in the documentation.

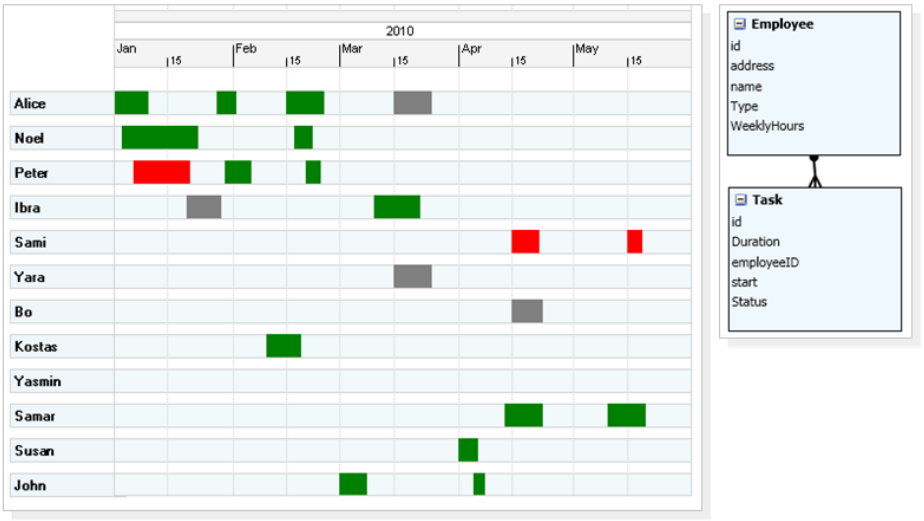
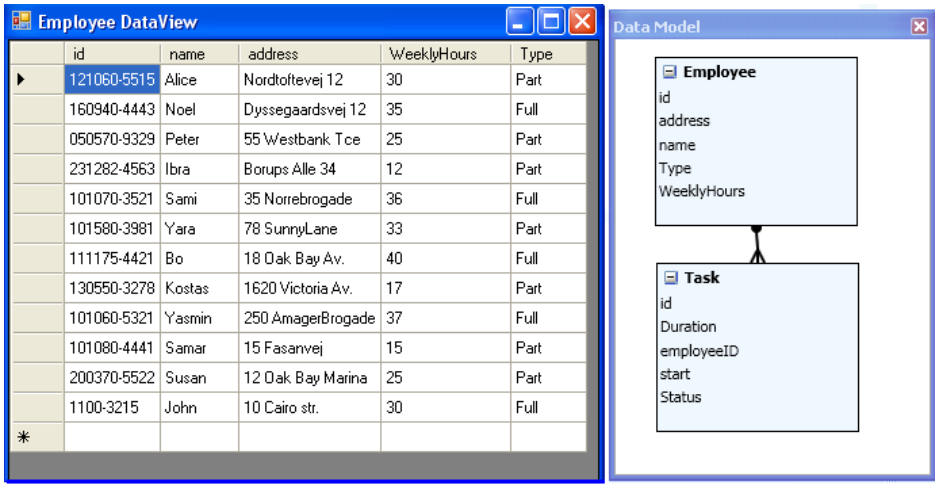


Figure 1.2: An employee task plan visualization. The model of the visualization data is on the right.



	id	name	address	WeeklyHours	Type
▶	121060-5515	Alice	Nordtoftevej 12	30	Part
	160940-4443	Noel	Dyssegaardsvej 12	35	Full
	050570-9329	Peter	55 Westbank Tce	25	Part
	231282-4563	Ibra	Borups Alle 34	12	Part
	101070-3521	Sami	35 Norrebrogade	36	Full
	101580-3981	Yara	78 SunnyLane	33	Part
	111175-4421	Bo	18 Oak Bay Av.	40	Full
	130550-3278	Kostas	1620 Victoria Av.	17	Part
	101060-5321	Yasmin	250 AmagerBrogade	37	Full
	101080-4441	Samar	15 Fasanvej	15	Part
	200370-5522	Susan	12 Oak Bay Marina	25	Part
	1100-3215	John	10 Cairo str.	30	Full
*					

Figure 1.3: Double clicking the employee table (box) shows a sample of the table

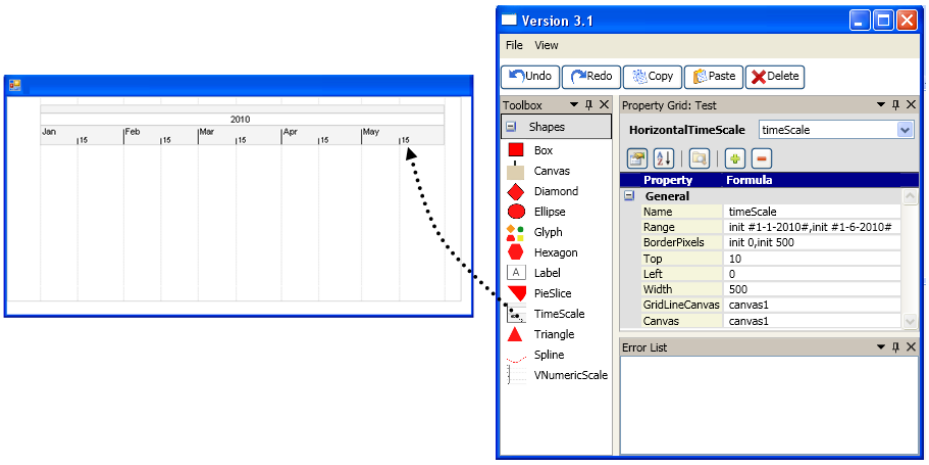


Figure 1.4: Dragging a time scale visual object to the design panel

1.1.1 Example

Objective: Kim is a Uvis experienced designer. She wants to create the visualization in Figure 1.2 with Uvis. The visualization shows a task plan for employees. The employees are shown as labels on the left. The employee tasks are shown as green, red, and grey boxes. Each colour represents a task status: green for done, red for cancelled, and grey for postponed. The tasks are aligned to the employees and horizontally positioned according to their start time.

The data behind the visualization come from two tables: `Employee` and `Task`.

Kim starts building the visualization in this fashion:

- **Getting familiar with the data:** She familiarizes herself with the data she wants to show. She sees tables `Employee` and `Task` in the data model. She double clicks the `Employee` box, and takes a look at a sample of the `Employee` table (Figure 1.3.)

- **Showing time:** To show time, Kim drags a horizontal time scale from the toolbox and drops it on the visualization form (Figure 1.4.)

  In the property grid, she sets the following properties of the time scale:

  Range: `#1-1-2010#, #1-6-2010#`

  Width: `500`

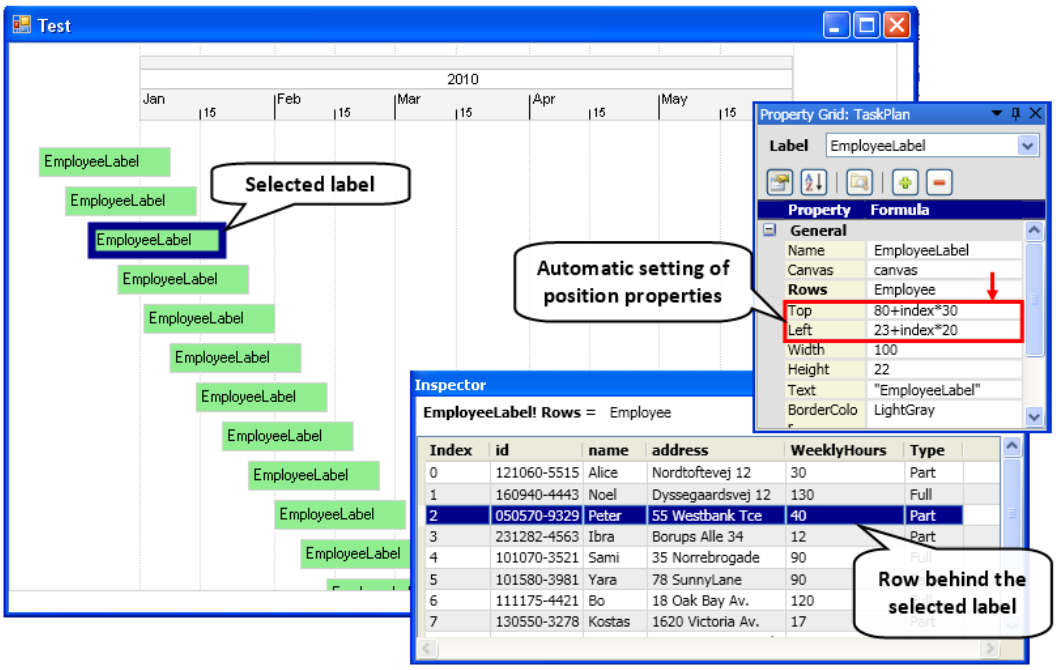


Figure 1.5: Connecting `EmployeeLabel` to data

This makes the time scale display the period of time between January and June 2010 in 500 pixels. She names the scale `hScale` to be able to refer to it later on.

- **Creating a label per employee:** To show labels of employees, Kim drags a label from the toolbox and drops it in the top left area, and names it `EmployeeLabel`.

  To create a label for each employee, Kim sets the following `Rows` property of `EmployeeLabel` in this way:

  Rows: `Employee`

  As a result, Uvis creates as many employee labels as there are rows in the `Employee` label. Uvis positions the labels like a staircase (Figure 1.5.) This cognitive aid explicitly shows that many visual objects were created. Further, Kim can now select an employee label and inspect the data row behind it, and vice versa (Figure 1.5.)

  How does Uvis position the labels like a staircase? Prior to defining the `Rows` property, the label's `Top` and `Left` values were 80 and 23 (the position where Kim

dropped the label.) Upon defining the `Rows` property, Uvis sets the following `Top` and `Left` formulas automatically:

Top: `80 + index*25`

Left: `23 + index*25`

The `Top` formula consists of numbers and `index`. The *index* is the label number. The first label's index is 0, the second is 1, and so on. The `Top` formula means: The first label's top is 80 + 0*25 (80), the second labels top is 80 + 25 (105), and so on. The `Left` formulas works in the same way. The result is that the labels cascade like a staircase.

To gain some understanding of how the calculation happens, Kim can select (click) the `Top` property, and the inspector will show all the `Top` values and the values of sub-expressions (i.e. `index`.)

- **Showing data from a table:** To show the employee names on the labels, Kim selects any employee label, and changes the following `Text` formula:

  Text: `Employee.name`

  The `Text` formula navigates to an `Employee` row and takes its `name` field. The result is that the labels now show employee names.

- **Showing visual objects that meet a criterion:** To only show employees who work more than 25 hours per week, Kim specifies the `Rows` property in this way:

  Rows: `Employee where WeeklyHours>20`

  The result is we only see employees with weekly work hours greater than 20.

- **Showing related data:** Kim wants to show the employee tasks as boxes. The tasks reside in the `Task` table. The `Task` table has a many-to-one relationship with the `Employee` table.

  First, Kim drags and drops a `Box` object. Second, she specifies the following formulas for the `Rows` and `Parent` properties:

  Parent: `EmployeeLabel`

  Rows: `parent-<Task`

The `Parent` formula means: Create a `Box` object for each parent (`EmployeeLabel`) object. The `Rows` formula means: Start in the `Employee` row connected to `EmployeeLabel` (the `Parent`). The join (`-<`) operator symbolizes a one-to-many crow's foot in the data model (Figure 1.2). Now navigate along the crow's foot to the `Task` table. The result is the related `Task` rows. Uvis creates `Box` objects that correspond to the rows.

- **Aligning a visual object to the time scale:** Kim wants to align the boxes representing tasks to the time scale according to their start time. She selects a task box, and defines the following `Left` property formula:

  Left: `hScale!Position(Task.start)`

  The `Left` formula means: Navigate to the time scale object (`hScale`). Call its `Position` function with `Task.Start` as a parameter. The result is that the time scale calculates the horizontal position of the task boxes according to their start time (`Task.Start`.)

- **Making a property depend on a condition:** To make the task colour represent the status, Kim defines the following formula for the `BackColor` property:

  BackColor: `Task.Status="done"? Green : Task.Status="cancelled"?`

  `Red : Gray`

  The `BackColor` formula looks at the field `Task.Status`. If it is done, make the box green. If it is cancelled, make the box red. Otherwise, make the box grey.

- **Checking the correctness of the visualization:** To check that the visualization shows the right data in the right way, Kim selects several employee labels, looks at the connected rows, and checks all the `weeklyhour` values. They all are greater than 20. This looks right. She moves on, and selects a task box. She looks at the connected row, and checks whether `Task.Status` is done or cancelled, and compares the status against the box colour. Kim moves on, and selects a box, compares the `Task.Start` value against the visual position of the box. It looks right too. Kim is now confident that her visualization is correct.

1.2 Thesis Statement and Research Contributions

My hypothesis is as follows: *It is possible to create custom visualizations with spreadsheet-like formulas, and savvy designers can learn how to refine the custom visualizations.*

This dissertation describes the following four primary contributions to the field of information visualization:

- The first contribution is a mechanism of creating custom visualizations with Uvis spreadsheet-like formulas. The visualizations cover several categories: time oriented, radial, hierarchical, etc.

- The second contribution is a visualization system (Uvis) that allows savvy designers to build formula-based visualizations with the drag-drop-set-property approach. The system provides cognitive aids that makes the process of building and checking a custom visualization easy to learn. The system has been iteratively designed based on feedback from savvy designers.

- The third contribution is a preliminary experimental evaluation with six potential savvy designers. The evaluation assesses how easy it is to learn the Uvis approach. The evaluation concludes that savvy designers can learn the basics of the Uvis approach.

- The fourth contribution is a usability analysis of several visualization tools. It highlights the striking differences between the existing approaches and Uvis.

1.3 List of Publications

- Soren Lauesen, *Mohammad A. Kuhail*, Kostas Pandazos, Shangjin Xu, and Mads B. Andersen. A drag-drop-formula tool for custom visualization. Submitted to IVAPP 2013.

- *Mohammad A. Kuhail* and Soren Lauesen. Customizable Visualizations with Formula-linked Building Blocks. In GRAPP/IVAPP, pages 768 (771, 2012.)

- *Mohammad A. Kuhail*, Kostas Pandazo, and Soren Lauesen. Customizable Time-Oriented Visualizations. In ISVC (2), pages 668 (677, 2012.)

- *Mohammad A. Kuhail*, Kostas Pantazos, and Soren Lauesen. The Inspector: A Cognitive Artefact for Visual Mappings. Submitted to IVAPP 2013.
- *Mohammad A. Kuhail*, Soren Lauesen, Kostas Pantazos, and XU Shangjin. Usability Analysis of Custom Visualization Tools. Submitted to SIGRAD 2012.

1.4 Organization of the Dissertation

The rest of the dissertation is organized as follows.

An overview of the existing approaches to visualization construction. Also, a survey of the relevant academic and commercial visualization and data analytic tools is given in Chapter 2.

I substantiate that it is possible to express custom visualizations with formulas as follows:

- The principles of Uvis formulas are explained through an example. This is followed with principles ensuring that Uvis performs sufficiently (Chapter 3.)
- A collection of formula-based custom visualizations are presented. This is followed with a discussion about the expressiveness and limitations of Uvis formulas (Chapter 4.)

I refined Uvis to make sure it is easy to learn for savvy designers as follows:

- I carried out several usability studies with savvy designers. The studies resulted in a refined version of Uvis. The initial and refined version of Uvis are presented. In particular, the cognitive aids that support the designers that resulted from the usability studies are presented (Chapter 5.) Furthermore, the usability studies with savvy designers are summarized (Chapter 6.)

I substantiate that savvy designers can learn how to refine custom visualizations as follows:

- Usability analysis of four tools including Uvis is presented. The analysis compares the tool approaches using a custom visualization, and evaluates them using the cognitive dimensions of notations (12).

- An evaluation study that was carried out with seven savvy designers is presented.

Finally, the benefits and limitations of the Uvis system, an outline of future work, and a summary of contributions and findings are presented.

2

Background

This chapter provides an overview of the existing approaches to visualization. The chapter describes each approach and assesses whether it is accessible to savvy designers and suited for custom visualizations. The visualization reference model (Section 2.1) is used where relevant to review how each approach supports visualization construction. The existing approaches can be divided into charting tools (Section 2.2.1), analytical and exploratory tools (Section 2.2.2), custom Visualization Tools (Section 2.2.3), and programming languages (Section 2.2.4). A summary of the existing approaches is given (Section 2.2.5).

2.1 Visualization Reference Model

One of the most famous models that describes how designers create visualizations is the visualization reference model ((13), (14)). The model decomposes the visualization design into three steps (Figure 2.1): First, raw data is transformed into structured data (e.g. tables) that can be further transformed by filtering, sorting, etc. (*data transformations*). Second, the data is mapped into visual structures (*visual mappings*). This step is considered the most crucial step for visualization effectiveness and expressiveness (15). Third, visual structures are mapped into interactive views (*view transformations*). Chi showed that the visualization reference model (or data state model) can characterize the majority of visualization techniques through a taxonomy of visualization techniques.

The model is used to analyse the visualization systems in the following section.

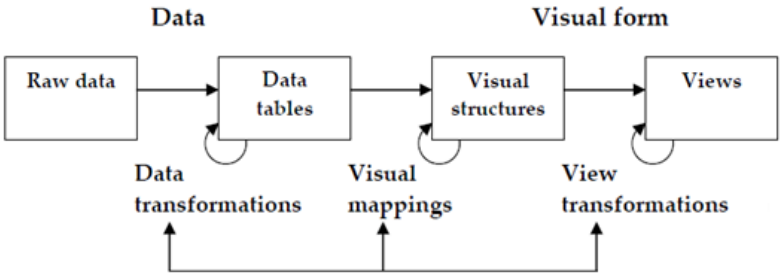


Figure 2.1: Visualization Reference Model

2.2 Approaches to Visualization

2.2.1 Charting Tools

One of the most popular tools for creating standard visualizations (e.g. bar charts) are charting tools such as MS Excel, Google spreadsheets (16), and Many Eyes (17). They are easy to use, and designers can create visualizations that correspond to predefined templates with a few clicks.

In Excel and Google spreadsheets, data are defined manually in cells. However, it is not easy to transform data (e.g. filter, group, etc.). This must be done by computing new cells. Visual mappings are made by selecting the cells to be visualized and choosing a visualization that shows it. Designers do not have full control over how visual objects show data. It is automatically handled by the system.

ManyEyes is a Java-Applet-based visualization platform. Designers create a visualization with three simple steps. Designers choose or provide a data set (usually a table), choose a predefined visualization, customize and publish it. Again, customization is very limited.

To sum up, charting tools are accessible to *novice designers*, designers with limited IT skills that correspond to using basic MS office applications and web browsers. However, the tools are not suited for custom visualizations.

2.2.2 Analytical and Exploratory Tools

Some data analytical and exploratory tools such as Spotfire (4), Tableau (18), and Omniscope (19) allow more data exploration than charting tools. They provide more

visualization templates and functionalities. For instance, they allow conditional colouring, sizing, etc.

Visual mappings are made by selecting predefined visualizations for selected data and changing some settings for selected visual objects such as "Size by" or Colour by".

Tableau is a commercial data analytical tool that is based on Polaris (20). Tableau helps designers to explore relational data through visualization. Designers drag and drop ordinal and quantitative fields onto axis shelves to create visualizations. As a result, Tableau creates a visualization showing data from the fields. Tableau also employs interaction techniques such zooming, and filtering. However, designers are limited in customizing the visual output of the system.

Spotfire supports designers with a predefined number of visualizations (e.g. Line charts) to analyse and interact with relational data. Furthermore, designers can create visualizations using data from a number of data sources, such as ODBC/JDBC source, flat files, xml files, etc. Like Tableau, Spotfire allows limited customization. Advanced customization, though, can be obtained programmatically.

Like Tableau and Spotfire, Omniscope creates visualizations based on predefined templates. Again, the designer does not have full control over the find building blocks of the visualization.

To sum up, these tools are more expressive than charting tools. However, designer's control over the resulting visualization is still limited, making the tools unsuited for the design of custom visualizations. For instance, a visualization like the Lifelines (3) can not be made.

2.2.3 Custom Visualization Tools

The research community has produced several visualization systems that support custom visualizations. Examples include InfoVis (21), Improvise (22), Prefuse (5), Flare (23), Protovis (6), and D3 (24). Only a few of these tools (e.g. Improvise and Protovis) use development environments that assist designers in data transformations and visual mappings. Figures 2.2 and 2.3 summarize the features that a representative set of these tools provide for data transformations and visual mappings.

InfoVis is a visualization toolkit that supports the creation of advanced visualizations such as trees and parallel co-ordinates. It provides a rich set of visual objects, and a framework for managing data structures like tables, graphs, and trees. To create

	InfoVis	Prefuse	Improvise	Protovis (Protoviewer)
Data Structures	■ Tables, Trees, etc.	■ ✓ Prefuse.data Table, Graph, Tree, etc.	■ ✓ Relational data	■ ✓ Associative arrays
Environment	□ N/A	□ N/A	■ ✓ Table view ✓ Schema view	■ ✓ Table view
Filter	■ **Function:** applyDynamicQuery in **class** FilterColumn	■ **Class:** Filtering SQL-like expressions, Predicates	■ **Expression:** Filtering Expressions (Filters)	▨ **Function:** JS filter
Sort	■ **Function:** Sort	■ **Class:** (e.g. Sort)	■ **Expression:** Sort expressions (Sorts)	▨ **Function:** JS syntax (e.g. sort)
Aggregate	▨ No explicit support	■ **Function:** Max, min, etc.	■ **Function:** Group, Max, Avg, etc.	■ **Function:** Nest, Max, Avg, etc.

Legend: ■ Supported ▨ Indirectly supported □ Not supported

Figure 2.2: Features provided by several custom visualization tools for data transformations

a visualization, the infoVis designer writes java-based code that refers to the infoVis framework (e.g. functions, constants, etc.)

Infovis provides data transformation mechanisms. For instance, data (columns) can be filtered using `dynamicQuery` types. There are many types (subclasses) of dynamic queries. For example, the `StringSearchDynamicQuery` can be used to search for a string in a column.

InfoVis provides specialized and primitive visual objects. To make a visual property (e.g. Height) show data, the designer can bind the property to a column using `setVisualColumn` function. To show data by colour, four types of classes can be used (e.g. `CategoricalColor`, `NominalColor`, etc.). InfoVis supports basic time-oriented visualizations such as time lines using a specialized visual object (`Axis`). Likewise, hierarchical data or data that require complex layout algorithms are supported by specialized visual objects.

An advantage of InfoVis is that some interaction mechanisms (e.g. `Fisheyes`) are easy to incorporate. It is just a visualization option. However, custom interaction requires in-depth programming.

		InfoVis	Prefuse	Improvise	Protovis (Protoviewer)
Visual objects	**Primitives**	■ Node(Circle, Ellipse, etc.)	■ Java Shape (Ellipse, etc)	■ Glyph (Rectangle, Oval, etc.)	■ Mark (Dot, Bar, Wedge, etc.)
	Specialized	■ AxisVisualization, TreeVisualization, etc.	■ Graph, TreeMap, etc.	■ BarChart, MatrixView, etc.	□ N/A
Environment		□ N/A	□ N/A	■ ✓ WYSIWYG ✓ selection	■ ✓ WYSIWYG ✓ selection
Visual mappings		■ **function:** ✓ setVisualColumn	■ **class:** ✓ action	■ **expression:** ✓ projections.	■ **expression:** ✓ Anonymous ✓ functions
Presentation Type	**Abstract** (1D, 2D, Multi D)	■ **visual objects:** ✓ Axis ✓ MatrixAxisVisualization	■ **class:** ✓ AxisLayout	■ **visual objects:** ✓ ScatterPlot ✓ PlaneView	■ **visual objects:** ✓ Bar, Dot **class:** ✓ scales
	Geographical	□ N/A	□ N/A	■ **visual objects:** ✓ PlaneView	■ **visual objects:** ✓ GMAP
	Temporal	■ **visual objects:** ✓ Axis	■ **class:** ✓ AxisLayout	■ **visual objects:** ✓ PlaneView	■ **class:** ✓ scales
	Tree	■ **visual objects:** ✓ Tree ✓ TreeMap	■ **visual objects:** ✓ Tree ✓ TreeMap	□ N/A	■ **class:** ✓ layout
	Network	■ **visual objects:** ✓ Graph	■ **visual objects:** ✓ Graph **class:** ✓ ForceDirectedLayout	□ N/A	■ **class:** ✓ layout

Legend: ■ Supported ▨ Indirectly supported □ Not supported

Figure 2.3: Features provided by several custom visualization tools for visual mappings

In summary, InfoVis supports useful visualizations, but the designer needs in-depth knowledge of the various abstractions (e.g. classes, functions). Designers can combine the abstractions to create custom visualizations or programmatically extend the abstractions. The approach requires in-depth tool and programming knowledge to create custom visualizations.

Prefuse is a visualization toolkit suited for advanced visualizations (e.g. tree maps, sunburst, etc.). It provides modules (e.g. functions, layout classes, etc.) suited for various visualization tasks. To create visualizations, the designer writes Java code that uses the modules.

Prefuse supports several aspects of data transformations. For instance, to filter a table, the designer can pass a textual logical expression to a table constructor, and the result is a filtered tuples (a row set).

Like InfoVis, Prefuse supports visual mappings by means of visual objects and modules. Prefuse provides simple geometric visual objects (e.g. rectangles, ellipses, etc.) and advanced visual objects that are suited for specific visualizations such as trees and graphs. To make the visual objects show data, the designer uses separate classes (actions) that map data columns to visual properties. The designer passes the visual property, and the data column to be mapped in the action constructor. There are many actions. Some actions (e.g. `EncoderAction` and `ItemAction`.) can show data conditionally since they map the data if a condition (Predicate) is met. Other actions support temporal data (e.g. Axis), and can encapsulate complex algorithms (e.g. `ForceDirectedLayout`). Further, Prefuse provides layout classes that can be used to position or resize visual objects. For instance, `ForceDirectedLayout` is a class that positions visual objects in a graph based on the force directed layout.

Prefuse allows easy incorporation of interaction mechanisms. For instance, interactive controls (e.g. drag, zoom, etc.) can be added to the display.

In summary, Like InfoVis, Prefuse uses many abstractions that designers have to know. The separation of actions from the visual objects and their properties can facilitate the management of code and allow reuse, but might increase the gap between the problem and the solution (Normans gulf of execution (7)).

Flare borrows many of its concepts from Prefuse, but supports web-based visualizations. It is a visualization toolkit written in ActionScript. This toolkit supports designers with a variety of simple and advanced visualizations. Designers define the

properties of the visual objects (e.g., position, shape, colour), and write imperative commands to create the visualization. Designers can also define new operators and visual objects. However, solid programming is required.

Improvise is a visualization system that mainly supports coordinated visualizations. The visual properties can show data using declarative expressions. The expressions can be conditional, logical, mathematical, etc. Designers use a development environment to create a visualization. They navigate from panel to panel to accomplish visual mappings. Each panel has a distinct purpose. For instance, one panel shows the available visual objects and their properties. Another panel shows the variables that can be used in expressions.

For data transformations, Improvise provides a table view for the to-be-visualized tables. The tables can be filtered using `Filters` expression. The designer composes an expression by choosing logical operators (e.g. `>`, `<`, AND, etc.) from a combo box. The resulting expression is shown as a tree. To make the expression operands refer to data fields, the designer assigns a variable to an expression operand and binds it to a field in another panel. Sort and Group by expressions are created in a similar fashion.

To create a visual object, the designer chooses a visual object (`control`) from a list (Type list). Next, the designer chooses a visual property of the visual object from the `Properties` list, and creates `Projections` expressions that can map data to the property. The projections are created in a fashion similar to other expressions (e.g. Filters, Sort, etc.), and can contain mathematical or logical operators, and refer to functions and data fields. Improvise provides specialized visual objects that facilitate visual mappings. For instance, it supports time-oriented and geographical data using a specialized visual object `PlaneView`.

Improvise allows some interaction using interactive components such as sliders. The designer can link the interactive components with visualizations using shared variables. However, this requires navigating back and forth through a series of panels.

In summary, Notation-wise, Improvise use declarative programming. However, the environment forces the designer to use combo-boxes that have the expression elements. It is difficult to find the expression elements. Moreover, the longer the expression, the harder it is to create and read.

Protovis is a JavaScript-based visualization toolkit that uses a declarative domain specific language that can map data to geometric visual objects (e.g. bar, dot, etc.)

and their properties. The toolkit can be extended with a development environment called "Protoviewer" (25).

Data transformations are supported by Protoviewer and the toolkit. Protoviewer provides a table view for the to-be-visualized tables. The tables can be programmatically filtered or sorted using JavaScript `filter` or `sort` functions. Protovis provides a function `nest` to transform flat to relational (multi-dimensional) arrays. Furthermore, Protovis provides statistical functions such as `max` (maximum), `avg` (average) that can be applied on an array.

Visual mappings are supported as follows: To bind a visual object (mark) to data, the designer passes an array to property `data`. To let a visual property (e.g. Height) represent data, the designer specifies a declarative expression (an anonymous function). The expressions can contain mathematical , logical, and conditional operators, reference to functions, and array columns. Protovis evaluates the expressions for each visual object, and the designer does not need to specify any loops. Protovis provides non-visual objects (scales) that support temporal data. The scales generate ticks data that can be used to draw ticks. Protovis provides layout classes (e.g. `Treemap`) that encapsulate complex algorithms, and support hierarchical visualizations such as trees.

Protovis supports interaction. However, it is much like event-driven programming. Even worse, the interactive components (e.g. combo boxes) are often separate HTML objects that are not part of the specifications.

To sum up, Protovis mostly uses declarative rather than imperative programming. This simplifies the effort required by the designers since they specify what the visualization should be rather than how it is constructed. Unlike Prefuse, Protovis expressions are directly associated with the visual properties. However, the specifications in Protovis remain program-like, and the designer often needs to define variables and worry about the sequence of doing things.

D3 is a JavaScript library for manipulating documents based on data. It borrows a lot of its concepts from Protovis, but is more expressive since it leverages web standards. It can be used to create custom visualizations, but the specifications are program-like.

2.2.4 Programming Languages

Several programming languages provide general purpose graphics APIs such as GDI+ (8) and Java 2D (9), and Processing (26). The APIs provide low-level building blocks

such as lines, curves, and ellipses. Such building blocks can be combined in numerous ways to compose visualizations. However, since they are general-purpose languages, it is tedious and hard to construct visualizations with this approach. Moreover, this approach requires programming skills that many visualization designers do not have.

The programming languages can be integrated with development environments like NetBeans (27), Eclipse (28), and MS Visual Studio (10). Providing cognitive aids, the environments can facilitate the development. For instance, the environments highlight the erroneous parts of the code, and provide suggestions while the developer is writing the code (Auto-completion). Still, these environments are designed to help programmers while coding, not designers while designing a visualization.

Processing is a programming language that can be used to construct interactive advanced visualizations. It is very expressive, and designers have full control over the fine building blocks of a visualization. However, it requires imperative programming, loops, etc. Processing has a development environment that allows designers to type the visualization specifications and view the outcome.

To sum up, the programming languages are very expressive but accessible only to *expert designers*, designers with solid programming skills.

2.2.5 Summary

Figures 2.5 and 2.4 summarize the findings in section 2.2. Charting tools are easy to use but inflexible. In comparison, analytical tools require more training since they are more expressive. They are accessible to non-programmers, but are still not suited for custom visualizations. The existing visualization tools have not been rigorously evaluated with savvy designers. They are more expressive than analytical tools. However, despite providing visualization abstractions, visualization tools are less accessible to savvy designers than analytical tools since they require program-like specifications. Programming languages are more expressive than visualization tools but are only accessible to expert designers (programmers).

An evaluation study showed that present visualization tools do not support savvy designers in constructing advanced visualization (29)

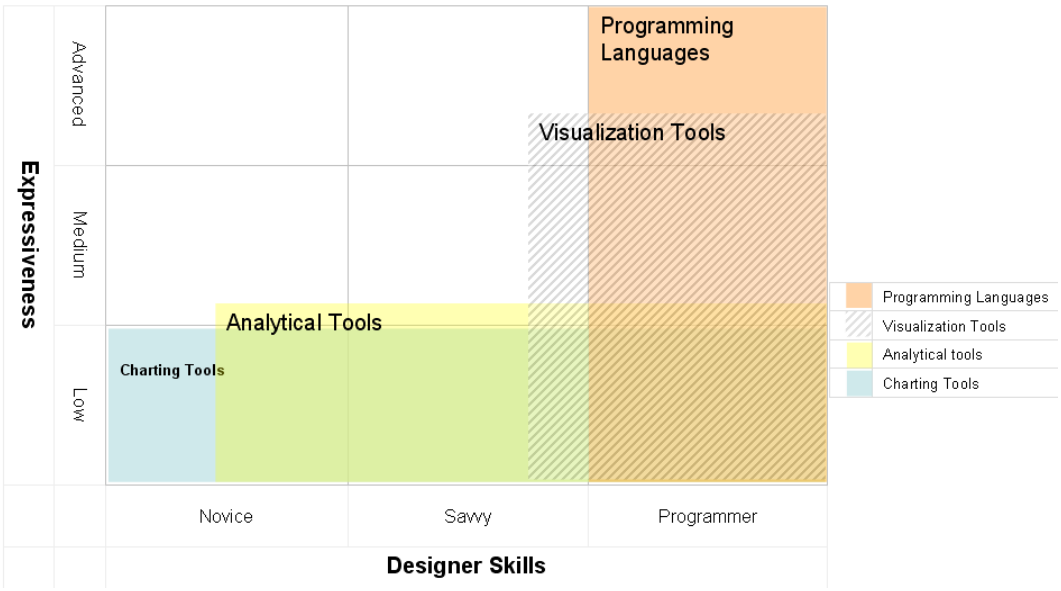


Figure 2.4: Summary of the existing approaches

		Spreadsheets (e.g. Excel)	**Analytical Tools** (e.g. Spotfire)	**Custom Visualization Tools**	**Programming Languages** (e.g. Java, C#)
Notation	Predefined templates	✓	✓		
	Visual objects			✓ Primitive and specialized	✓ Primitive
	modules			✓ Layout, helper functions, classes	
	Declarative programming			✓ (Protovis, Improvise)	
	Imperative programming			✓ (Prefuse, Flare, InfoVis)	✓
Environment	Direct manipulation				✓ (Microsoft Visual studio and NetBeans)
	WYSIWYG	✓		✓ (Improvise and Protoviewer)	
	Table view	✓	✓	✓ (Improvise and Protoviewer)	
	Dialog-Driven			✓ (Improvise)	
	Auto-completion				✓ (Microsoft Visual studio and NetBeans)
	Error highlighting				✓ (Microsoft Visual studio and NetBeans)
Accessibility to savvy designers		Accessible	Accessible	Not evaluated	Not accessible
Visualization Customizability		Very Low	Low	High	Very high

Figure 2.5: Summary of the existing approaches

3

Uvis Formulas

3.1 Introduction

Uvis formulas are declarative spreadsheet-like expressions that can bind visual objects to data and make their properties represent the data.

This chapter presents the principles of Uvis formulas as follows: First, the Uvis architecture is presented (section 3.2.) The architecture explains the context in which Uvis formulas operate. Second, the visual objects, their properties, and their functions are presented (section 3.3.) Third, the formula principles are explained using an example (section 3.4.)

Of course a useful visualization has to perform sufficiently. The chapter discusses the design principles that ensure that Uvis performs sufficiently. The principles are followed with performance figures (section 3.5.)

3.2 Architecture

Figure 3.1 shows the Uvis system architecture. A *Connection description file* (vism file) is a text file with vism extension (Figure 3.2). It contains descriptions of connection to one or more databases, the relationships of interest, and the foreign and primary keys behind the relationships. Further, it contains a reference to a visualization form to be shown at start up. A data architect or a programmer writes these descriptions. The Uvis kernel reads this file, establishes connection to database, and prepares the relationships that designers can use.

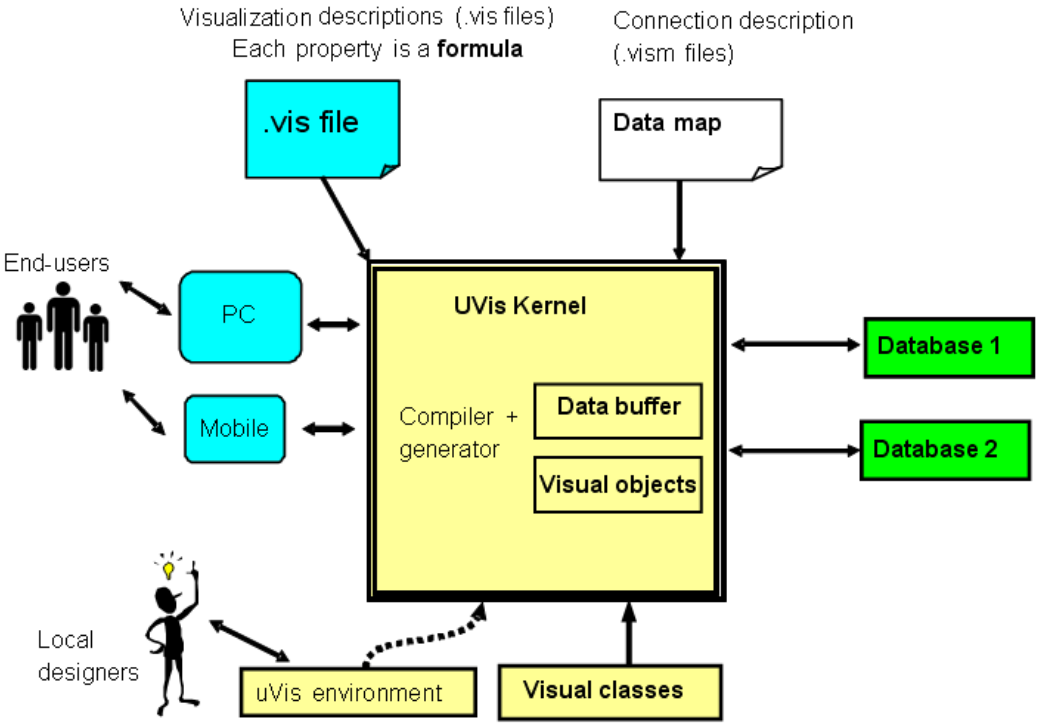


Figure 3.1: Uvis architecture

```
DataView: design
TimeMode: simulated, 28-02-2011 14:38
ScreenSize: default
StartUpForm: Test
-----------------------------------
Database: Provider=Microsoft.Jet.OLEDB.4.0;Data Source=Tasks.mdb
-----------------------------------
Table: Employee
Task: many, join Task on Task.employeeID= Employee.id
-----------------------------------
Table: Task
Employee: one, join Employee on Employee.id=Task.employeeID
```

Start-up visualization form

Connection

Table and relationships

Figure 3.2: An example of a vism file

A *visualization description file* (vis file) is a text file with vis extension. Each vis file corresponds to a visualization form, and contains formulas that specify properties of visual objects. Visual objects are the building blocks of a visualization. *Visual classes* are the blueprints from which the visual objects are created. The *Uvis compiler* compiles the vis file, and stores data which the visualization shows in the *data buffer*.

In principle, designers can build visualizations by textually editing vis files with a notepad. However, cognitive barriers will be high. The *development environment* provides cognitive aids to help designers. Chapter 5 explains the environment.

Currently, Uvis can run on a pc. Once it is installed, end-users can run a visualization form by clicking a vism file. From this form, they can navigate to other forms.

3.3 Visual Objects

Visual objects are the building blocks of a visualization. Figure 3.3 shows examples of the visual objects Uvis provides. Some of them are based on .Net UI elements (e.g. `Button`, `Textbox`, etc.). Others are *geometric visual object* such as `Triangle`, `Ellipse`, etc. They are inspired by Cleveland (30)) recommendations, and can be used to show data as position, colour, orientation, etc. Furthermore, I designed specialized objects that are commonly used in visualizations. For example, `VNumericScale` is a specialized object that shows a vertical numeric scale.

3.3.1 Properties

Visual objects have properties. The properties can bind the visual objects to data and determine their appearance and behaviour. Each property can have a formula that computes its values.

There are four kinds of properties:

- **Built-in properties** are defined by the visual object. They bind visual objects to data and determine the visual object appearance (e.g. position, size, colour, etc.). For consistency, some built-in properties are common for all visual objects. Figure 3.4 and Figure 3.5 show examples of the common built-in properties.

  Other built-in properties are specific to some visual objects. For instance, a `PieSlice` has `InnerRadius` and `OuterRadius` as specific properties (Figure 3.6.)

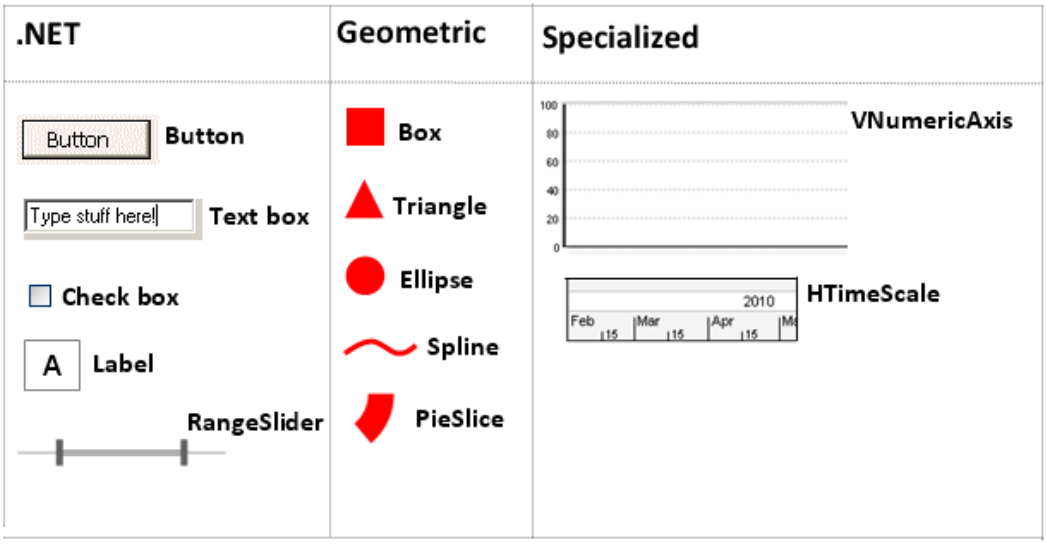


Figure 3.3: Examples of Uvis visual objects

`Rows`	Connects visual objects to data.
`Parent`	Shares the data of a visual object with another visual object.
`Top`	The distance, in pixels, between the top edge of a visual object and the top edge of the form.
`Left`	The distance, in pixels, between the left edge of a visual object and the left edge of the form.
`Right`	The distance, in pixels, between the right edge of a visual object and the left edge of the form.
`Bottom`	The distance, in pixels, between the bottom edge of a visual object and the top edge of the form.
`Height`	The height of the visual object.
`Width`	The width of the visual object.
`BackColor`	The background colour of the visual object.
`BorderColor`	The border colour of the visual object.

Figure 3.4: Examples of common built-in properties

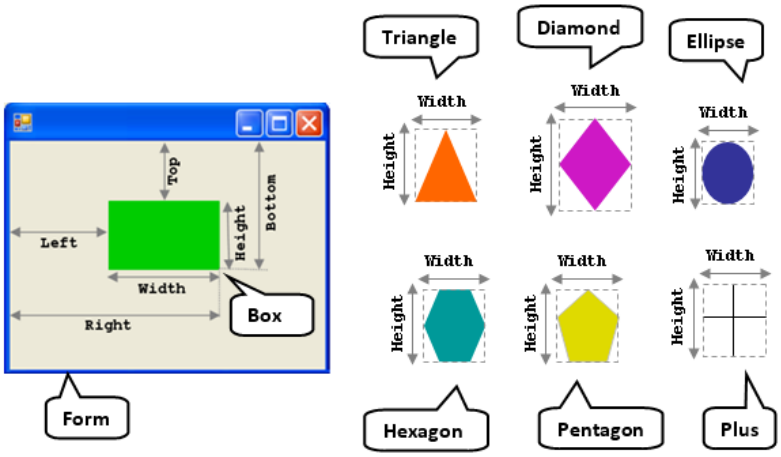


Figure 3.5: Size and position properties of some visual objects

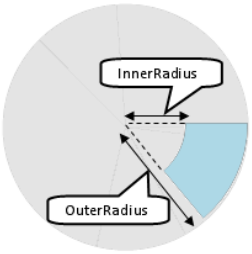


Figure 3.6: Visual-object-specific properties

`UpperCase(String)`	Returns a copy of this String in uppercase
`SQRT(Number)`	Returns the square root of a number
`MAX(Field)`	Returns the maximum value of a field in a visual object bundle.
`MAX(Property)`	Returns the maximum value of a property in a visual object bundle.
`Total(Field)`	Returns the sum value of all fields in a visual object bundle.
`Total(Property)`	Returns the sum value of all properties in a visual object bundle.
`AVERAGE(Field)`	Returns the average value of all fields in a visual object bundle.
`AVERAGE(Property)`	Returns the average value of all properties in a visual object bundle.
`Refresh()`	Check for changed data and update all visual objects that have changed.

Figure 3.7: Examples of utility functions provided by Uvis

- **Designer properties** are added by the designer. As an example, the designer may write a complex formula in such a property and let other properties refer to it rather than repeat it. As another example, the designer may define a property without a formula. It serves as a variable that keeps track of whether the end-user has clicked this control.

- **Event properties** do not have a formula but one or more statements that are performed when the event happens. As an example, the `Click` event for a `Button` may contain an `OpenForm` statement that opens another form.

3.3.2 Functions

As other tools, Uvis has utility functions (e.g. math, string, and aggregation functions). Further, it has a `Refresh` function that causes Uvis to explicitly check for changed data and update all visual objects that have changed. Figure 3.7 shows examples of these functions.

Some visual objects have built-in functions that formulas can call. As an example, `HTimeScale` provides functions that can translate a point in time into a pixel position, and vice versa. This allows a visual object to position itself according to a point in time.

3.4 Formula Basics

In general, a formula is an expression that takes some data as input and computes a result. In designing the formulas, we wanted them to be somehow like spreadsheet formulas. Spreadsheet formulas have been successful with savvy and novice users. They are declarative since they specify what the result of the computation should be rather than how it should be done, and where the result should be stored. Further, they are sequence-free, and do not have loops.

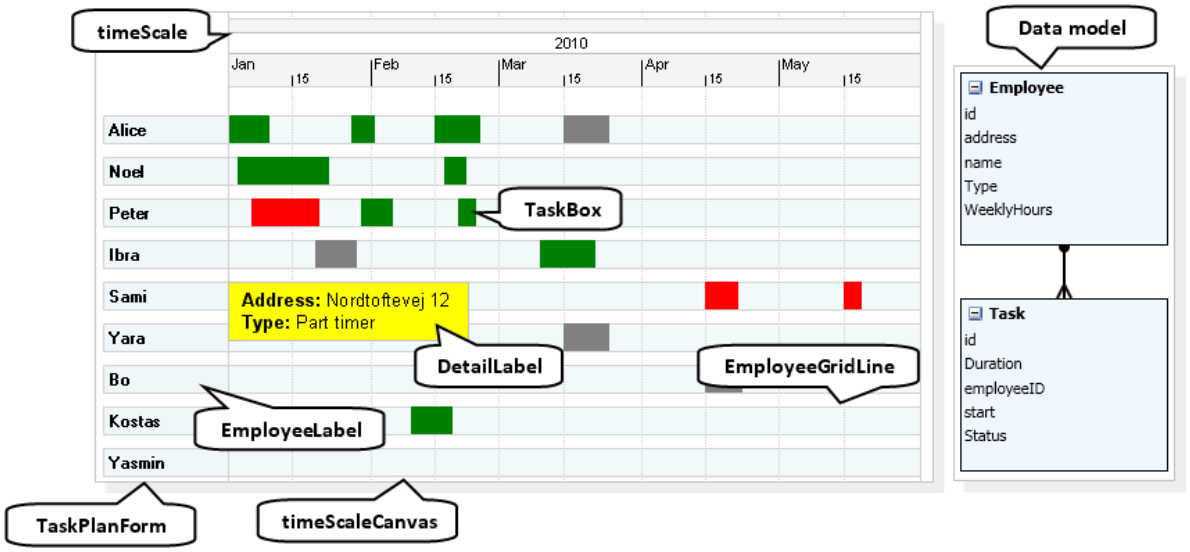
The formula basics are explained through the example in Figure 3.8. The visualization in the example is an employee task plan. The employees are shown as a vertical list of labels. They are based on data from table `Employee`. Only employees who work more than 20 hours per week are shown. A time scale on the top displays the period of time between January and June 2010. The employee tasks are shown as boxes. The boxes use the time scale to position themselves horizontally according to the task start time. The width of the boxes represents the task duration. The task boxes are vertically positioned according to the employee the task belongs to. A box is green if the task has a "done" status, and red if the status is "cancelled". Otherwise it is grey. If an end-user clicks an employee label, a label showing more details about the employee pops up. Further, if an end-user drags the time scale to show more or less time detail, the task boxes are automatically updated to reflect the new time scale.

3.4.1 Visual Containers

By default, visual objects (e.g. `EmployeeLabel`) are shown on the form (i.e. `TaskPlanForm`). They can also be shown on a canvas. This helps to clip visual objects that go beyond the canvas boundaries. We specified that the time scale and objects mapped to it (e.g. `TaskBox` objects) are shown on a canvas (`timeScaleCanvas`). Hence, when an end-user drags the time scale (to show more or less time details), the objects mapped to the scale do not go beyond the canvas borders. Therefore, they do not overlap with other visual objects out of the canvas (e.g. `EmployeeLabel`).

3.4.2 Connecting visual objects to data

Uvis formulas can connect visual objects to tables in relational databases using formulas. For instance, we connected `EmployeeLabel` (Figure 3.8) to the `Employee` table



Form	TaskPlanForm
Width	Init 670
Height	Init 520

Canvas	timeScaleCanvas
Top	0
Left	100

HTimeScale	timeScale
Canvas	timeScaleCanvas
Range	#1-1-2010#, #1-6-2010#
Width	500
Top	10
Left	0
Dragged	Refresh()
Dragging	

Default

Label	EmployeeLabel
Rows	Employee where weeklyHours>20
Top	70+index*(Height+10)
Left	10
Text	Name
Click	TaskLabel!Selected=index, Refresh()

Box	TaskBox
Canvas	timeScaleCanvas
Parent	EmployeeLabel
Rows	Parent -< Task
Left	timeScale!Position(Task.Start)
Right	timeScale!Position(Start+Duration)
Top	Parent!Top
BackColor	Task.Status = "Done" ? Green : Task.Status = "Cancelled" ? Red : Gray

Label	DetailLabel
Canvas	timeScaleCanvas
Selected	init -1
Top	EmployeeLabel[Selected]!Top Default 0
Left	EmployeeLabel[Selected]!Right Default 0
Text	Bold("Address: ") & EmployeeLabel[Selected].Address & NewLine() & Bold("Type: ") & EmployeeLabel[Selected].Type
DoubleClick	Visible= Not Visible
Visible	Selected >= 0

Box	EmployeeGridLine
Parent	EmployeeLabel
Top	Parent!Top
Width	500

Figure 3.8: A task plan visualization

with the following formula:

Rows: `Employee`

As a result, Uvis generates a corresponding SQL statement and sends it to the database engine. Uvis retrieves a row set and creates a *bundle* of `EmployeeLabel` objects that correspond to the row set. Each object is *connected* to a row.

Transforming data: Uvis formulas can transform the retrieved data. For instance, they can filter, order, and join the tables. As an example, we connected `EmployeeLabel` to only employees who work more than 20 hours per week with this formula.

Rows: `Employee Where weeklyHours>20`

The `Rows` formula retrieves the employees who fulfil the criterion in the `Where` clause.

Uvis formulas can show related data. For instance, we made `TaskBox` objects show the tasks related to the employees labels with these formulas.

Parent: `EmployeeLabel`

Rows: `Parent -< Task`

The `Parent` formula means: Create a `TaskBox` object or bundle for each parent (`EmployeeLabel`) object. The `Rows` formula means: Start in the `Employee` row connected to `EmployeeLabel` (the `Parent`). The `-<` symbolizes a one-to-many crow's foot in the data model (Figure 3.8). Now navigate along the crow's foot to the `Task` table. The result is a bundle of rows, one for each of the employee's tasks, and a corresponding bundle of `TaskBox`es.

The `Rows` formula corresponds to the following SQL statements.

```
SELECT Employee.ID, Employee.Name, Task.Start, Task.Duration, Task.Status
FROM ( (SELECT Employee.id FROM Employee WHERE [weeklyHours] > 20 ORDER BY
[name]) AS nested1 ) LEFT join Task on Task.employeeID= nested1.id"
```

`Rows` formulas are more compact than SQL statements. The designer does not have to worry about specifying primary and foreign keys. The data architect has specified them in the vism file. Furthermore, the designer does not specify the fields to select. Uvis collects the selected fields from property formulas that refer to them.

To sum up, `Rows` formulas can bind visual objects to data, and transform the data. This corresponds to the step of *data transformations* in the visualization reference model.

Chapter 4 gives examples of more advanced SQL-like formulas. For instance, formulas that can refer to visual properties.

3.4.3 Property Formulas

Each property can have a formula that specifies how to compute its value. Uvis evaluates the formula for each visual object in the bundle and sets the property with the resulting value.

The formulas can be mathematical, logical, and conditional. Further, they can refer to data fields, properties, and functions. Let us look at examples of different formulas.

- **Formulas referring to properties:** We positioned the `EmployeeLabel` objects like a vertical list with this formula.

  Top: `70 + Index*(Height+10)`

  The `Top` formula refers to `Height` and `Index`. `Height` is an `EmployeeLabel` property. Its value for all `EmployeeLabel`s is 20. `Index` is the visual object number in the bundle. The first visual object's index is 0, the second is 1, and so on. Thus, the `Top` value of the first `EmployeeLabel` object is `70 + 0*(20+10)`. This corresponds to `70`. The second `Top` value is `70 + 1*(20+10))` This corresponds to `100`, and so on.

  The result is that the employee labels are positioned like a vertical list.

- **Formulas referring to functions and data fields :** The `TaskBox` objects align themselves to the time scale with these formulas.

  Left: `timeScale!Position(Task.Start))`

  Right: `timeScale!Position(Task.Start + Task.Duration)`

  The `Left` formula means: Navigate to `timeScale`. Call its `Position` function and ask it to translate the start time of the task (field `Task.Start`) to a pixel position. Use this position as the `Left` property.

  Notice that the designer does not have to write the table name before the field name, but it helps if there are two identical field names in different tables.

  The `Right` formula adds the task duration (in days) to the task start, and asks `timeScale` to calculate the position. The result is that each `TaskBox` object is stretched correctly in the time dimension.

  The bang (`!`) operator navigates from a visual object to a property or a function while the dot (`.`) operator navigates from a visual object to a field. In principle,

we could have used the dot operator for both cases, but it introduces ambiguities if there are identical field and property or function names. However, the designer can still use a bang operator to navigate to a field, but the compiler looks for a property or a function first. Similarly, the designer can use a dot operator to access a property, but the compiler gives priority to a field.

- **Formulas referring to parent properties:** We positioned the `TaskBox` objects according to their parents (`EmployeeLabel`) with these formulas.

  Top: `Parent!Top`

  The `Top` formula means: Navigate to the parent (`EmployeeLabel`) object and take its `Top` value. The result is that the task boxes are vertically aligned to the employee labels they belong to.

- **Conditional formulas:** We made `TaskBox` objects show task statuses as colour with this formula.

  BackColor: `Task.Status = Done ? Green : Task.Status = Cancelled ? Red : Gray`

  The `BackColor` formula means that if field `Task.Status` is "done", make the box green. If it is "cancelled", make the box red. Otherwise, make the box grey.

- **Addressing properties of other visual objects:** We will illustrates how a formula can address properties in other visual objects. We defined a label (`DetailLabel`) that shows up upon clicking an `EmployeeLabel` object. The label shows the employee address and type.

  We gave `DetailLabel` these property formulas

  Selected: `Init -1`

  Visible: `selected >= 0`

  Top: `EmployeeLabel[selected]!Top Default 0`

  Left: `EmployeeLabel[selected]!Right Default 0`

  Text: `Bold("Address: ") & EmployeeLabel[Selected].Address & NewLine() & Bold("Type: ") & EmployeeLabel[Selected].Type Default ""`

We added property `Selected`. It is not a built-in property, but a *designer property*. `Init -1` means that `Selected` is initially -1, but the value can change as a result of end-user actions. When the end-user selects an employee label, `Selected` should become the `Index` of the label.

The `Visible` formula says that the label should be visible when something is selected (`selected >= 0`). Initially it will be invisible

The `Top` formula says: Navigate to the bundle of employee labels. Take the label with the index given by `Selected`. Take its `Top` property value. If this doesn't work, for instance because nothing has been selected, use the default value and make `Top`= 0. The `Left` formula works in a similar manner. The result is that the label is aligned according to the employee label.

The `Text` formula says: Show "address :" in bold. Concatenate it with what follows. Navigate to the bundle of employee labels. Take the label with the index given by `Selected`. Take its `Address` field value, and so on.

The `Top`, `Left`, and `Text` formulas are examples of addressing properties and fields in another visual object.

To sum up, Uvis formulas use the *navigation principle* to address data fields, visual objects, properties, and functions. Uvis navigates from component to component to get the result. The `Top` formula above is an example of this. The formula navigates to a bundle of visual objects, then to a visual object to the property of that visual object.

Using this principle and having different kinds of expressions (e.g. logical, mathematical, etc.), Uvis formulas can make properties show data. This corresponds to the step of *visual mappings* in the visualization reference model.

3.4.4 End-user Data and Interaction

We only lack one thing to make the selection run: a way to set `Selected`. This is done through the `EmployeeLabel` object. It should respond when the end-user clicks it. We defined an event handler property for it:

Click: `DetailLabel!Selected=index, Refresh()`

When the end-user clicks an employee label, Uvis performs the statements in the `Click` formula. As a result, `Selected` will become the index of the clicked employee label. The

statement `Refresh()` asks Uvis to re-compute all formulas and redraw visual object where a property value has changed.

In contrast to ordinary property formulas, an event handler formula cannot be evaluated at any time. The event handler is evaluated only when the end-user does something.

Let us look at a case where the designer does not need an event handler formula to implement interaction. Consider this default formula in the `timeScale` object.

Dragged: `Refresh()`

`Dragged` is an event that is triggered after the end-user has just dragged the time scale. The `Dragged` formula means: Call `Refresh()` when the event is raised. As a result, Uvis will re-compute all the formulas, and sets new property values where needed. For instance, the `TaskBox` objects will update their horizontal positions since they use the `Position` function provided by `timeScale`.

A *default formula* is a formula specified in the visual object by default. It corresponds to the most likely behaviour. However, a default formula can be changed or deleted by the designer. For instance, we might want the `TaskBox` objects to update their positions as the end-user is dragging the time scale. To accomplish that behaviour, the designer deleted the default `Dragged` formula, and defined this formula.

Dragging: `Refresh()`

`Dragging` is an event that is triggered as the end-user is dragging the time scale. The `Dragging` formula means: Call `Refresh()` when the event is raised. The result is that `TaskBox` objects will update their horizontal positions as the end-user is dragging the time scale.

To sum up, Uvis event-handler formulas specify what happens upon end-user actions. Designers do not always have to write event-handler formulas.

Interaction with the visualization can change the view. For instance, it can view more information on demand, zoom in a visualization to see more details, or filter out uninteresting data. This corresponds to the step of *view transformations* in the visualization reference model.

Step		Time (ms)
Compilation	200 formulas	43
Creation	146 visual objects	133
SQL queries	8 queries, 140 rows	401
Rendering	146 visual objects	94
Total (ms)		**671**

Time to open form

Step	Time (ms)
Creation	46
Rendering	32
Total (ms)	**78**

Time to refresh form

Figure 3.9: Performance results of the lifelines example

3.5 Performance

To evaluate Uvis performance, we used profiling tools to measure the time that Uvis takes to open or refresh a visualization form. The data were collected using Windows XP OS, with a 2.66 GHz Intel Core 2 Duo processor and 2.66 GB RAM, and a local MS Access database. Averages of 10 measurements per result were taken.

Figure 3.9 shows the performance of a visualization inspired by the Lifelines (3) created with Uvis. The visualization is shown in Figure 3.10. The total time to open the screen is 0.6 seconds including 0.4 seconds to make 8 queries to the database. The time to refresh the entire form is 0.07 seconds.

Compilation time is the time Uvis needs to compile all the formulas in the visualization form. *Creation time* is the time Uvis needs to create all visual objects according to data rows, compute all formulas, and set the properties. *Refresh time* is calculated this way: Recompute all formulas, re-query the database if an SQL statement has changed, set all visual properties to the new computed value (whether it has changed or not), and update the screen accordingly. *SQL-query time* is the time needed to send an SQL query and retrieve the data. *Rendering time* is the time needed to render the visual objects on the screen.

Figure 3.11 shows the performance of several other visualizations created with Uvis. More details about performance results can be found at (31).

In the following sections, we will discuss some principles that ensure adequate performance.

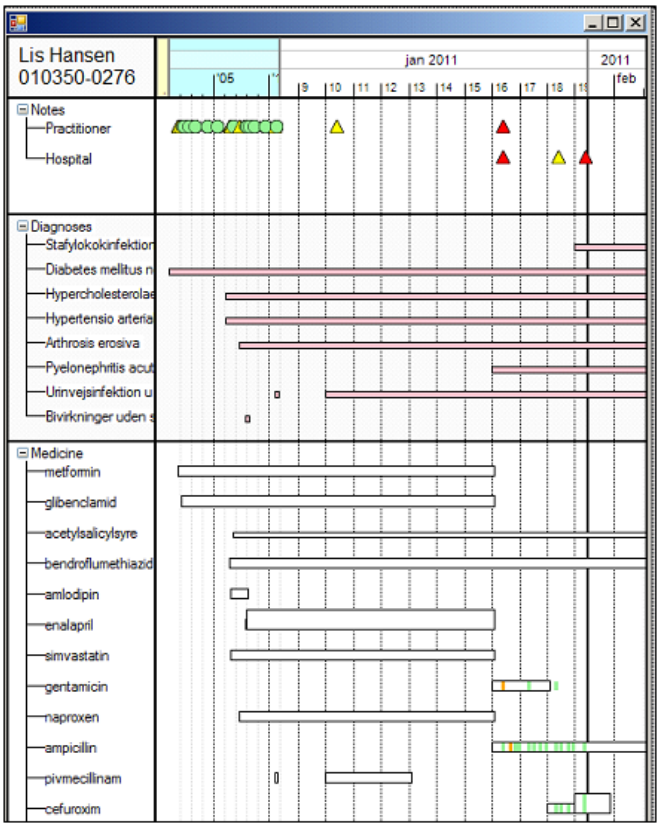


Figure 3.10: A visualization inspired by LifeLines

	Bar chart (Company sales)	**Custom pie chart** (passenger statistics)	**Custom line chart** (city temperature)	**Indented trees** (medicine tree)	**Tile Maps** (Hotel Guests)	**Spiral Graph** (website hit rates)
Number of visual objects	**1,000**	**2,000**	**3,000**	**5,000**	**10,000**	**20,000**
Creation time (ms)	135	192	262	456	735	1,710
Rendering time (ms)	5	7	5	9	7	11

Figure 3.11: Performance of visualizations created with Uvis

Number of rows	One SQL for All Rows	One SQL per Row
100	670 ms	4,594 ms
1,000	687 ms	46,357 ms
5,000	811 ms	265,383 ms
10,000	887 ms	443,946 ms
20,000	1,192 ms	956, 710 ms

Figure 3.12: Comparison of single-row queries against multiple-row queries

	GDI+ Box		.NET TextBox			
	Creation and Changing Time (µs)		Creation Time (µs)		Changing Time (µs)	
Number of objects	All objects	Per object	All objects	Per object	All objects	Per object
1	7.05	7.05	653	653	364	364
100	92.40	0.92	53,288	532	43,573	435
500	442.87	0.89	315,363	630	413,558	827
1,000	867.10	0.87	652,435	652	635,498	635
5,000	4,774.87	0.95	9,630,886	1,926	10,798,213	2,159
9,500	8,282.97	0.87	40,526,280	4,265	49,592,477	5,220

Figure 3.13: Performance of a GDI+ `Box` in comparison to a .NET `TextBox`

3.5.1 One SQL Query per Multiple Visual Objects

Rather than sending one SQL query per visual object, Uvis sends only one SQL query for all visual objects defined by a `Rows` formula. As an example, all objects of `EmployeeLabel` (Section 3.4.2) correspond to one SQL query. As another example, `TaskBox` objects correspond to one SQL query too.

The performance difference between sending one SQL per row and one SQL per multiple rows is immense especially for a large number of rows. Figure 3.12 shows the difference assuming the connection is established once for both SQL queries. The data were collected using MS Access and a table with 16 fields, 126,000 rows, and 44MB in size.

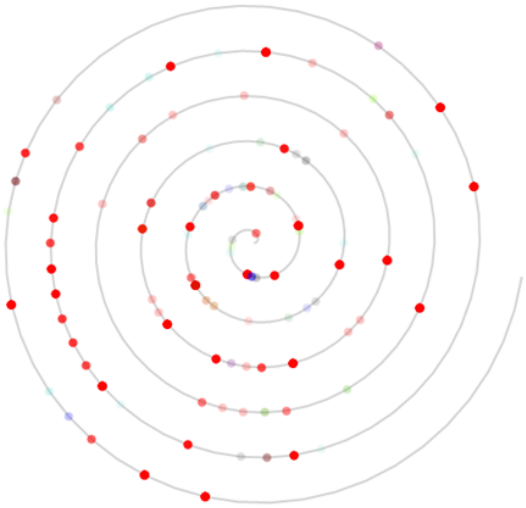


Figure 3.14: A visualization inspired by the Spiral Graph (1) containing 10,000 ellipses representing website hits

3.5.2 Fast GDI+ Shapes

Most Uvis visual objects, except for the .NET ones, are shapes based on GDI+ drawings (8). They are fast to draw, and they have fewer properties. Figure 3.13 compares the performance of a GDI+-based `Box` with a .NET-based. *Changing time* is the time needed to reposition the objects. It was not possible to create more than 9,500 .NET `Textbox` objects. The computer froze.

Number of objects	One-Cell Canvas			Multi-Cell Canvas		
	Creation Time (ms)	Interaction Time (ms)	Rendering Time (ms)	Creation Time (ms)	Interaction Time (ms)	Rendering Time (Ms)
2,000	1,358	50	25	1,275	2	45
6,000	2,131	90	56	2,355	2	46
10,000	2,839	60	98	3,423	2	44
14,000	3,539	100	110	5,141	2	44
18,000	4,545	110	133	7,670	2	46

Figure 3.15: Comparison of performance of a spiral visualization with one-cell canvas against multi-cell canvas

3.5.3 Multi-Cell Canvas

In the beginning, we only had a one-cell canvas. All visual objects were drawn on the canvas. Upon an end-user action, for instance, if the end-user clicks a visual object, Uvis compares the coordinates of all visible visual objects against the `Click` coordinates, and triggers a `Click` event on the shape of highest z-order (the shape on top). This performed reasonably with visualizations containing fewer than 2,000 shapes. However, it performed poorly with visualizations with more shapes. For instance, it would take more than a second to respond to an event.

A *cell-based canvas* was designed to speed up the interaction performance. The canvas is divided into cells where each cell is 32 X 32 pixels at most. Hence, the number of cells depends on the canvas width. When shapes are created or repositioned, they are classified according to which cell they belong to.

The multi-cell canvas has two advantages. First, when the canvas receives an end-user event, the co-ordinates of the event are checked against the cells, then compared against the shape boundaries that belong to the cell. The right shape with the highest z-order receives the event. Otherwise, the canvas does. Second, when a shape is repositioned, only the affected cells (where the shape was and where it will be) are re-drawn (rendered) rather than all the visual objects. I call this *partial rendering*. These advantages come at the cost of extra creation time due to the classification of objects.

To evaluate the effect of the multi-cell canvas on a visualization with relatively large number of visual objects, I created a visualization inspired by the Spiral Graph (1) (Figure 3.14). I varied the number of objects to see the difference. Figure 3.15 has the details.

4

Formula-Based Visualizations

4.1 Introduction

This chapter substantiates the *expressiveness* of Uvis formulas, the breadth of visualization ideas that can be expressed. First, the chapter explains how a selected collection of visualizations are made with Uvis. Second, the chapter discusses the expressiveness factors and limitations of Uvis.

Figure 4.1 shows an overview of the selected visualizations. The Task Plan visualization was explained in chapter 3. The rest of the visualizations have various characteristics. For instance, some have a radial layout while others have a linear one. Interaction-wise, some visualizations are based on the details-on-demand metaphor, and others allow end-user dynamic queries. The examples are not necessarily great visualizations, but illustrate the expressiveness of formulas.

Three papers explain more examples. The papers can be found at (32), (33) and (34).

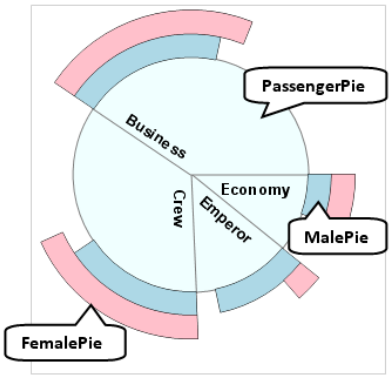
4.2 Example Visualizations

4.2.1 Passenger Statistics

Figure 4.2 shows an example of showing data using a radial layout. The example also uses a formula that sorts a table. It is a custom pie chart that represents the percentages of all passengers of several flying classes (e.g. Crew, Economy, etc.). The percentages are sorted by the number of passengers. The percentages of male passengers are shown

		Visualizations				
		Task Plan	**Passenger Stats**	**Train Schedule**	**Medicine Tree**	**Website Hits**
Uvis formulas	**1. Data Transformations** Filter a Table	✓				
	Sort a Table		✓			
	Join Two Tables	✓		✓	✓	✓
	2. Visual Mappings					
	Mathematical positioning	✓		✓	✓	✓
	Data field formulas	✓	✓	✓	✓	✓
	Visual property formulas	✓		✓	✓	✓
	Parent property formulas	✓	✓	✓	✓	
	Conditional formulas	✓		✓	✓	
	Logical formulas	✓				✓
	Sibling formulas		✓		✓	
	Children formulas			✓	✓	
	-= formulas			✓		
	Event-handler formulas	✓			✓	
Visualization Characteristics	**1. Relational**	✓		✓	✓	✓
	2. Hierarchal				✓	
	3. Time-Oriented	✓		✓		✓
	4. Interactivity Details on demand	✓				✓
	More or less details	✓			✓	✓
	Filter					✓
	Dynamic Queries					✓

Figure 4.1: An overview of the selected visualizations



Type	males	females	classID
Emperor	40	10	1
Business	70	80	2
Economy	20	20	3
Crew	60	70	1

Passenger Table

PieSlice	PassengerPie
Rows	Passenger Order By males + females
CenterX	200
CenterY	200
StartAngle	index=0? 0 : Me[index-1]!EndAngle
SweepAngle	360* (males + females) / (Total(males) + Total(females))
OuterRadius	100
Text	Type

Default

PieSlice	MalePie
Parent	PassengerPie
CenterX	Parent!CenterX
CenterY	Parent!CenterY
StartAngle	Parent!StartAngle
SweepAngle	360* males / (Total(males) + Total(females))
InnerRadius	100
OuterRadius	120

PieSlice	FemalePie
Parent	PassengerPie
SweepAngle	360* females / (Total(males) + Total(females))
InnerRadius	120
OuterRadius	140

Figure 4.2: Passenger statistics visualization

in light blue pie slices, while the female passengers are shown in pink on top of the male ones. The visualization is based on table `Passenger` with these columns: `Type` (e.g. economy, business, etc.), `males` (number of male passengers), `females` (number of female passengers).

We want to connect `PassengerPie` to the `Passenger` table. Further, the table should be sorted according to the number of male and female passengers. To accomplish that, we defined the following `Rows` formula of `PassengerPie`:

Rows: `Passenger Order By males + females`

The `Rows` formula retrieves a bundle of rows from the `Passenger` table. The rows are sorted by the number of male and female passengers. Uvis creates a bundle of `PassengerPie` slices that correspond to the rows.

Next, we set other visual properties such as `CenterX`, `CenterY`, and `OuterRadius` (Figure 4.3 shows the meaning of these properties).

Sibling formulas: The `PassengerPie` slices align next to each other with the following formula:

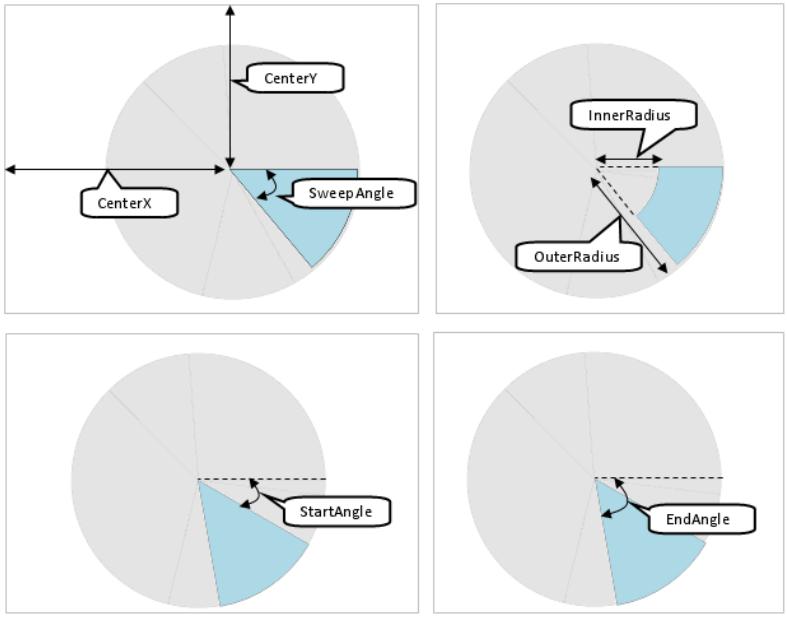


Figure 4.3: Pie Slice properties

StartAngle: `index=0?0:Me[index-1]!EndAngle`

The `StartAngle` formula means: If this is the first pie slice, the start angle is 0. Otherwise, navigate to my bundle. Get the visual object with `index-1`. Get its `EndAngle`. The result is that each pie slice's `StartAngle` is the previous pie slice's `EndAngle` except for the first slice (Figure 4.3). Consequently, the slices align next to each other.

Notice that `Me` refers to this visual object (corresponds to `this` in Java and C#) while `Me[]` refers a specific visual object in its own bundle . Thus, `index-1` accesses the previous visual object in the bundle.

The `StartAngle` formula is set by default in `PieSlice` objects. The slices commonly need to align next to each other. However, the designer can specify a different formula.

Referring to aggregate functions: Each pie slice's `SweepAngle` should represent the number of passengers for a particular class (e.g. Economic, Emperor, etc.). To accomplish that, the `SweepAngle` property is defined in this way:

SweepAngle: `360.0*(males + females) / (Total(males) + Total(females))`

`Total` is a function that calculates the sum of fields in the rows connected to a visual object bundle. The result is that `SweepAngle` represents the percentage of all passengers (`males` and `females`) for the different passenger classes in.

The `MalePie` and `FemalePie` are connected to the same data as `PassengerPie` objects, and can access the same fields (according to their `Parent` formulas). Hence, the `SweepAngle` formulas of `MalePie` and `FemalePie` show male and female passengers respectively.

4.2.2 Train Schedule

Figure 4.4 shows a train schedule visualization. The stations that the trains stop at are shown on the left. An hourly time scale shows the time from 4:00 AM till 12:30 PM. The train stop times are shown as dots connected with lines. Southern trains are shown in red while northern ones are shown in blue. The data come from tables `Station`, `Train`, and `StopTime`.

This visualization explains how to show line segments with Uvis. Furthermore, it explains how Uvis formulas navigate from data rows to visual objects. Let us look at the details.

To show the stations as labels, we connected `StationLabel` to the `Station` table, and positioned it vertically with the following formulas:

Rows: `Station`

Top: `78+0.7*Dist`

The `Top` formula positions the labels vertically according to the station distances from the start point (field `Dist`).

Next, to show the trains as labels, we connected `TrainLabel` to the `Train` table.

Showing curves: Uvis supports curves using a `Spline` visual object. A `Spline` represents a curve segment. A `Spline` has a start point (`StartX` and `StartY`) and an end point (`EndX` and `EndY`) (Figure 4.5). To connect the `Spline` objects to each other so they form a curve, the default specification is that the end point of a `Spline` is the start point of the next `Spline` in the bundle. The last `Spline`'s start point is the same as its end point. However, when a designer first creates a `Spline` , it is not connected to data. We still want it to look like a curve segment. The default specification in this case is that the end point is just 5 pixels to the top and to the right of the start point.

To show the train stops as curves, the designer defined the following formulas of `StopTimeSpline`:

Parent: `TrainLabel`

Rows: `parent -< StopTime`

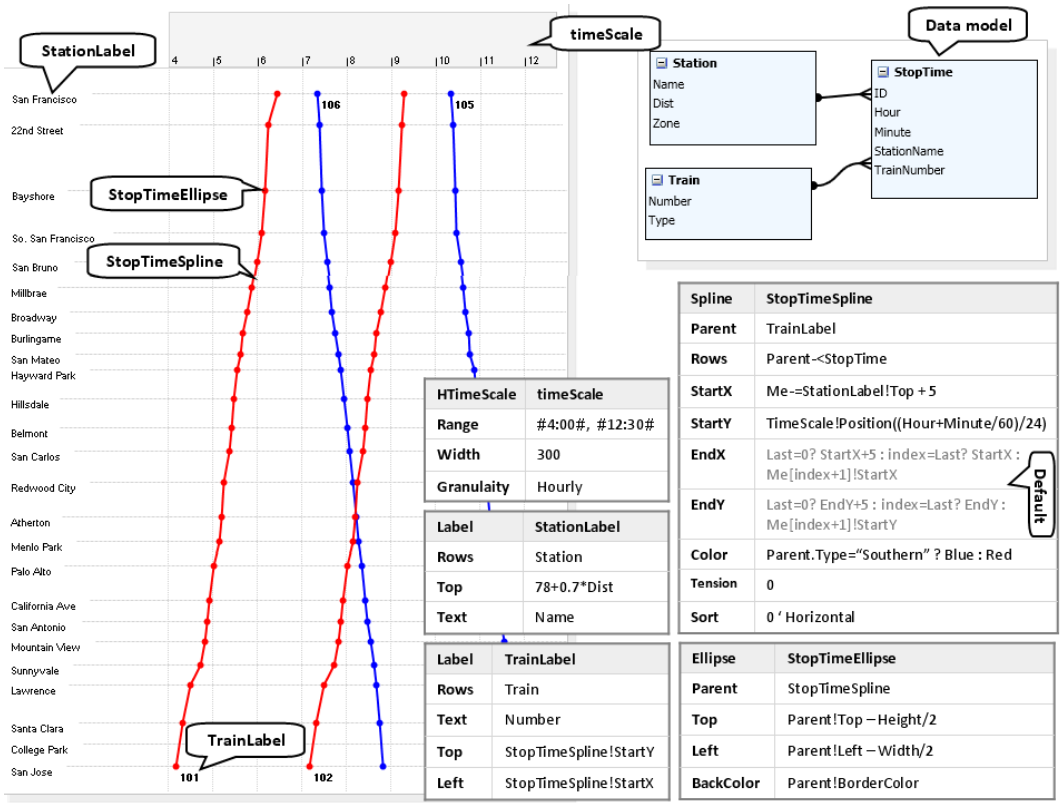


Figure 4.4: A train schedule visualization

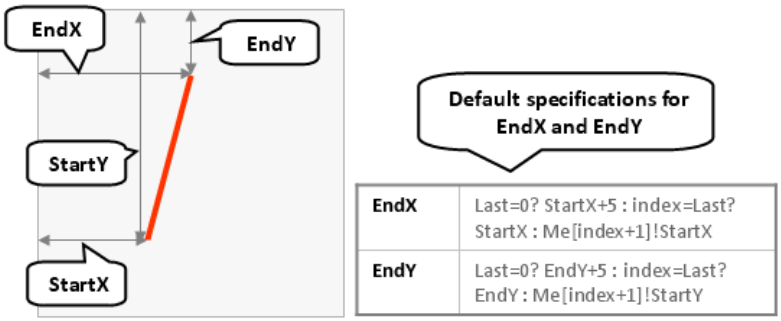


Figure 4.5: A spline specification

Left: `timeScale!Position((Hour+Minute/60)/24)`

Tension: `0`

The `Parent` and `Rows` formulas make the `StopTimeSpline` objects show the stop times of the trains.

The `Left` formula positions the `StopTimeSpline` objects in the time dimension using a `Position` function provided by `timeScale`. The `Position` function takes a `DateTime` or a `double` value as a parameter. In this case, it takes a `double` value representing the number of days.

The `Tension` property determines how much the spline segments bend. If the value of the tension parameter is 0, the spline uses segments that are straight lines. `Tension` accepts floating numbers from 0 to 1.

Navigating from data rows to visual objects: To align the `StopTimeSpline` objects to the stations, we defined the following formula:

Top: `Me-=StationLabel!Top`

The `Top` formula means: For the row connected to me (`StopTime` row), navigate to the `StationLabel` object that is related to the same row. Finally, use the label's top position as the stop time spline's top.

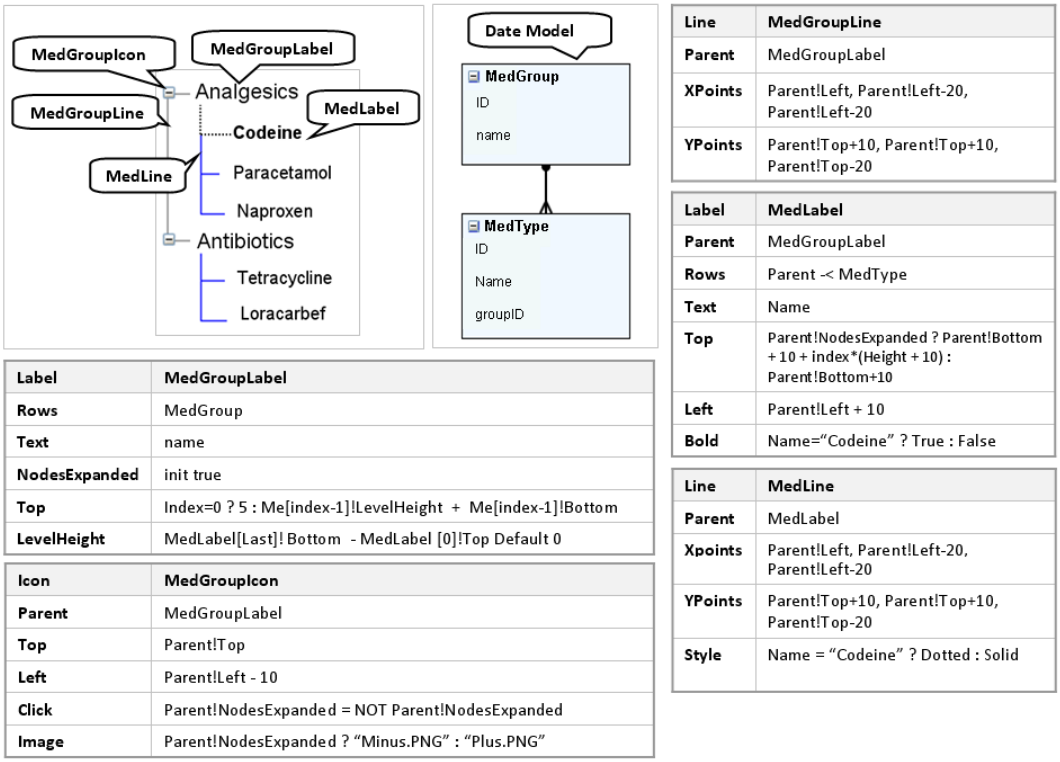
Notice that `StationLabel` is connected to the `Station` table and `StopTimeSpline` is connected to the `StopTime` table. Now notice that the `Station` table has a one-to-many relationship with the `StopTime` table. The relationship allowed Uvis formulas to navigate from the row of a `StopTimeSpline` object to the related `StationLabel` object.

4.2.3 Medicine Tree

Figure 4.6 shows a two-level interactive tree of medicines. The first level is the medicine group and the second is the medicines that fall under these groups. The end-user can collapse or expand the second level using expand/collapse icons.

This example demonstrates how Uvis formulas can express visual hierarchies. It may be challenging to construct for a savvy designer. It is also an example of interaction that shows more or less information on demand.

We construct the tree from primitive visual objects such as `Label`, `Icon`, and `Line`. The result is that every visual object can be customized. For instance, the label showing



Label	MedGroupLabel
Rows	MedGroup
Text	name
NodesExpanded	init true
Top	Index=0 ? 5 : Me[index-1]!LevelHeight + Me[index-1]!Bottom
LevelHeight	MedLabel[Last]! Bottom - MedLabel [0]!Top Default 0

Icon	MedGroupIcon
Parent	MedGroupLabel
Top	Parent!Top
Left	Parent!Left - 10
Click	Parent!NodesExpanded = NOT Parent!NodesExpanded
Image	Parent!NodesExpanded ? "Minus.PNG" : "Plus.PNG"

Line	MedGroupLine
Parent	MedGroupLabel
XPoints	Parent!Left, Parent!Left-20, Parent!Left-20
YPoints	Parent!Top+10, Parent!Top+10, Parent!Top-20

Label	MedLabel
Parent	MedGroupLabel
Rows	Parent -< MedType
Text	Name
Top	Parent!NodesExpanded ? Parent!Bottom + 10 + index*(Height + 10) : Parent!Bottom+10
Left	Parent!Left + 10
Bold	Name="Codeine" ? True : False

Line	MedLine
Parent	MedLabel
Xpoints	Parent!Left, Parent!Left-20, Parent!Left-20
YPoints	Parent!Top+10, Parent!Top+10, Parent!Top-20
Style	Name = "Codeine" ? Dotted : Solid

Figure 4.6: Medicine tree visualization

medicine Codeine is bold and the line connecting that particular label is dotted. Such customizability is difficult to obtain with present visualization tools.

Let us look at how we created the tree with Uvis.

Visual Hierarchy: To position the first and second levels as an indented tree, we defined these formulas for the first level (`MedGroup`) objects.

NodesExpanded: `init false`

LevelHeight: `MedLabel[Last]!Bottom - MedLabel[0]!Top Default 0`

Top: `Index=0 ? 5 : Me[index-1]!LevelHeight + Me[index-1]!Bottom`

`NodesExpanded` and `LevelHeight` are designer properties. `NodesExpanded` shows whether the second-level objects (`MedLabel`) are shown (expanded). `NodesExpanded` initially has a `false` value (i.e. the second-level objects are hidden.)

`LevelHeight` calculates the space the second-level objects occupy (`MedLabel` objects). The space is the distance between the first and last objects in the bundle. The space is zero if there are no second-level objects.

The `Top` of the first `MedGroup` object is 5. The rest of the instances are positioned below the sibling objects and their children objects. The result is that the first and second levels are positioned like a tree.

Interaction: To allow end-users to expand and collapse the second-level objects , we defined an `Icon` object (`MedGroupIcon`) and defined these formulas.

Parent: `MedGroupLabel`

Click: `Parent!NodesExpanded = NOT Parent!NodesExpanded`

The `Click` formula negates the `NodesExpanded` of the `MedGroupLabel` when the end-user clicks an icon. This collapses or expands its `MedLabel` objects.

`MedLabel` objects position themselves vertically with this formula.

Top: `Parent!NodesExpanded ? Parent!Bottom + 10 + index*(Height + 10)`
: Parent!Bottom+10

The `Top` formula means: if `Parent` (`MedGroupLabel`) objects are expanded, `MedLabel` objects position themselves vertically. Otherwise, they align on top of each other below their parents. This behaviour is different from the behaviour in present tools where the children nodes are completely hidden when they are collapsed.

Of course, we can still completely hide the children nodes by defining the following formula of `MedLabel` objects:

Visible: `Parent!NodesExpanded`

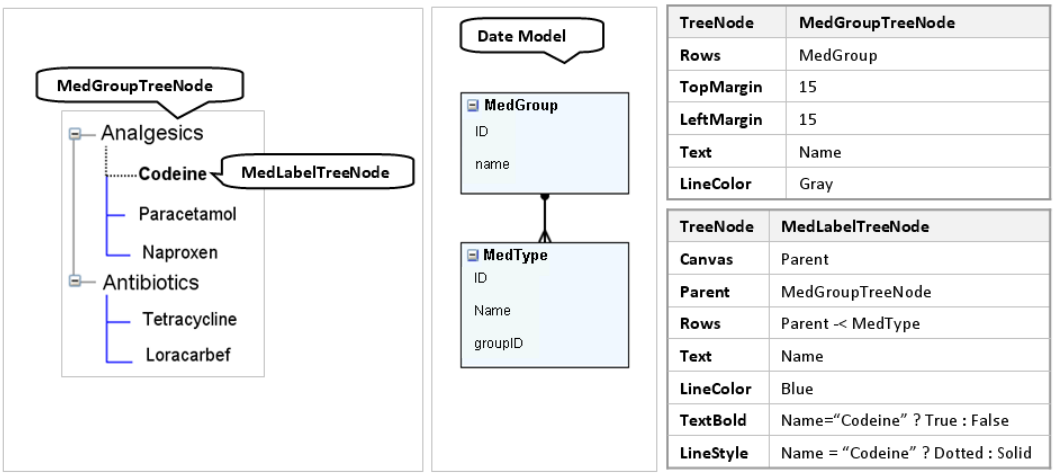


Figure 4.7: Medicine tree visualization with `TreeNode` objects

Customizing primitive visual objects: Now that the tree has been made, let us try to show the tree node Codein differently. First, to show the Codeine label in bold, we defined this formula of `MedLabel`:

Bold: `Name="Codeine" ? True : False`

To make the line connecting the Codeine tree node dotted, we defined this formula of `MedLine`:

Style: `Name = "Codeine" ? Dotted : Solid`

Constructing an indented tree with a specialized object: We can construct the medicine tree with much less effort with a specialized object called `TreeNode`. It is more customizable than similar objects in present tools, but it is still not as customizable as constructing an indented tree from primitive visual objects. Figure 4.7 shows the specifications of the medicine tree with `TreeNode` objects. The `TreeNode` objects position themselves, expand, and collapse automatically. The designer does not have to worry about these details.

4.2.4 Website Hits

Figure 4.8 shows an interactive visualization inspired by the Spiral graph (1). The visualization shows the hits on a website between 18 February 2007 and 24 February 2007 on a spiral. Each cycle in the spiral represents a day. The spiral starts from the

centre clockwise. The visualization is based on two related tables. `Page` is the website pages. `Hit` is the visitor's hits on the pages.

End-users can interact with the visualization in these ways: First, to magnify or shrink the spiral, end-users can change the spiral radius using a track bar. Second, they can un-check the pages when they do not want to see their hits. Third, they can search for the country the hits come from. This corresponds to *dynamic queries* since the visualization is constantly updated based on the end-user's changes, and queries are sent behind the scene.

Constructing the spiral: Uvis supports spiral graph visualizations with a `Spiral` object that displays cyclic time-oriented data on a spiral.

To define a spiral that covers a specific period of time and allow the end-user to change the spiral radius, we defined the following formulas for `WebsiteSpiral`:

Range: `#18-2-2007#, #24-2-2007#`

Radius: `RadiusTrackBar!Value`

`Range` is a property that determines the period of time the spiral covers. It is a two-item list property. The first item is the range start, and the second is the range end.

The `Radius` formula means: Navigate to `RadiusTrackBar` object. Take its `Value` property. The result is that the spiral radius gets updated when the end-user drags the track bar. The default behaviour is that `RadiusTrackBar` calls `Refresh()` when the value is changed. The designer, of course, can change that.

Dynamic Queries: To allow end-users to search for hits in a specific country. we defined the following formulas for `HitEllipse`:

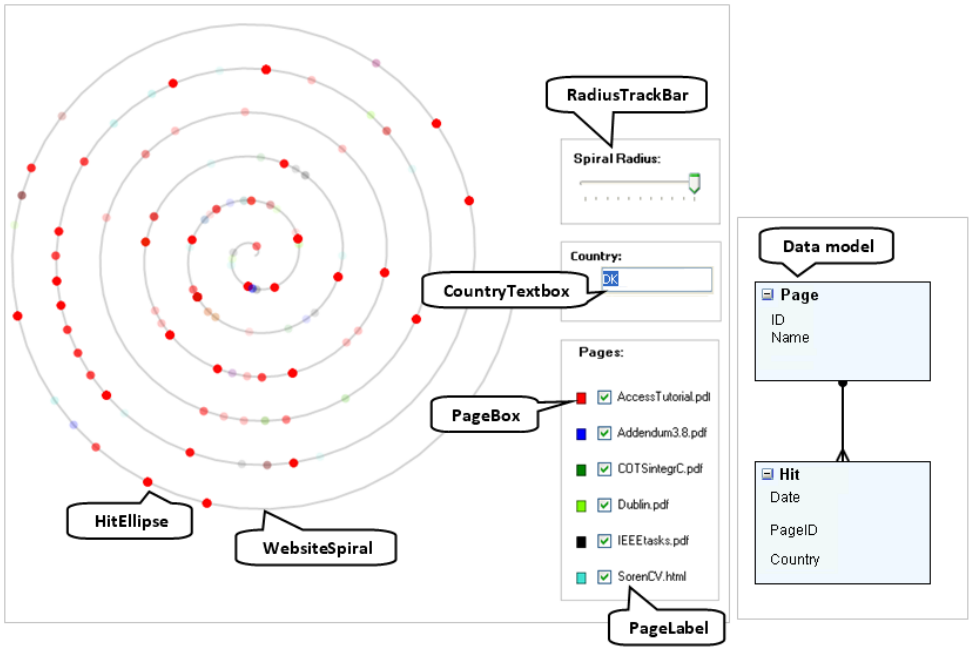
Parent: `PageCheckbox`

Rows: `parent -< Hit Where Country LIKE CountryTextbox!Text & "%"`

The `Rows` formula means: Start in the `Page` rows connected to the parent. Get the related `Hit` rows provided that the `Country` field starts with the text provided by the end-user through `CountryTextBox`. `CountryTextBox` calls `Refresh()` when its text changes.

Filtering out unnecessary items: To only show the hits that represent pages that have been checked by the end-user, we defined the following formula for `HitEllipse`:

Visible: `Parent!Checked`



Spiral	WebsiteSpiral
Range	init #18-2-2007#, init #24-2-2007#
Granularity	1, Day
Radius	RadiusTrackBar!Value
CenterX	200
CenterY	200

Checkbox	PageCheckBox
Rows	Page
Text	Title
Checked	Init True
PageColor	ColorScale(index)
CheckedChanged	Refresh()

Textbox	CountryTextbox
TextChanged	Refresh()

Box	PageBox
Parent	PageCheckBox
BackColor	Parent!PageColor

Ellipse	HitEllipse
Parent	PageCheckBox
Rows	Parent -< Hit Where Country LIKE CountryTextBox!Text & "%"
BackColor	Parent!PageColor
Top	WebSpiral!VPosition(Date) - Height/2
Left	WebSpiral!HPosition(Date) - Width/2
Visible	Parent!Checked
Alpha	50 'out of 255

TrackBar	RadiusTrackBar
ValueChanged	Refresh()

Default

Figure 4.8: Website hits Visualization

The `Visible` formula means: Make a `HitEllipse` object visible when its parent `PageCheckbox`is checked. `PageCheckbox` objects call `Refresh()` when the end-user checks or unchecks them.

Polar Positioning: To position `HitEllipse` objects according to the time they show, we defined the following formulas for `HitEllipse`:

Left: `WebSpiral!HPosition(Date) - Width/2`

Top: `WebSpiral!VPosition(Date) - Height/2`

The `Left` formula means: Navigate to the `WebSpiral` object. Call its `HPosition` function with the `Date` field as a parameter. `WebSpiral` provides `HPosition` and `VPosition` functions that calculate the horizontal and vertical positions of a point in time. Subtract half the ellipse's width to make its *centre* represent the point in time. The `Top` formula works in a similar fashion.

The result is that the ellipses are aligned to the spiral according to the time they represent.

Over-plotting: Since it is likely that many hits occur at the same time, we need a way o distinguish a few from many hits occurring at the same time. This is called the *over-plotting problem* (35). We solved the problem with the following formula for `EllipseHit`:

Alpha: `50 'out of 255`

The `Alpha` property represents the transparency component of a colour. Its value is 50 out of 255. `EllipseHit` objects are 19 % visible.

4.3 Other Visualizations

Figure 4.9 gives an overview of other visualizations that have been created with Uvis. Some of the visualizations are explained in (36), (37), and (32). Some of the visualizations were created using only primitive visual objects. For instance, the visualization inspired by CircleView (38) was created using `PieSlice` objects.

Other visualizations were created with specialized objects. For instance, the visualization inspired by the horizon graph (39) is created with `Area` objects that have a specialized layout property. The property can have a `"HorizonGraph"` value that supports the horizon graph visualizations.

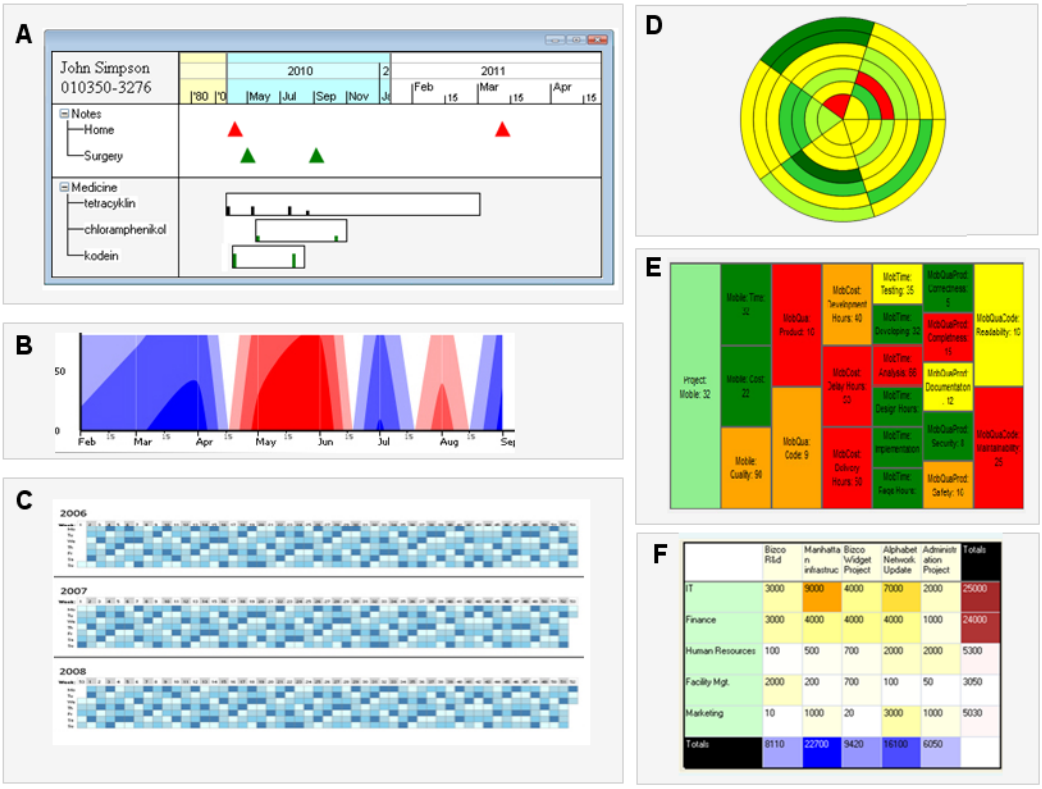


Figure 4.9: Other visualizations created with Uvis. (A) LifeLines. (B) Horizon Graphs. (C) Tile Maps. (D) CircleView. (E) Tree Maps. (F) Heat-map grid

Visualization		Lines of Code
Name	Inspired by	
Task Plan	Gantt charts	134
Passenger Stats	Custom pie chart	64
Medicine Trees (primitive)	Indented Trees	39
Medicine Trees (specialized)	Indented Trees	14
Train Schedule	Étienne-Jules Marey's Trains	81
Website Stats	Spiral Graph	98
Patient Record Analysis	LifeLines	119
Company Profits	Horizon Graphs	55
Hotel Guests Stats	Tile Maps	51
Stock Prices	CircleView	33

Figure 4.10: Lines of code needed to created several visualizations with Uvis

4.4 Lines of Code

Figure 4.10 shows the lines of code needed to create various visualizations with Uvis. Uvis formulas shorten the lines of code in many ways. For instance, `Rows` formulas are much more compact than SQL statements since they don't contain key nor `select` specifications.

In general, Uvis does many things behind the scene that shorten the specifications. As an example, Uvis creates objects that correspond to rows, evaluates property formulas and sets the values for properties of each visual object, updates property values when `Refresh` is called, etc.

Sometimes specialized objects can reduce the lines of code. For instance, creating intended trees with `TreeNode` requires considerably fewer lines of code than using primitive objects.

4.5 Expressiveness Factors

Uvis expressiveness depends on these factors:

1. **Referencing mechanism:** `Rows` formulas have the same expressiveness as SQL statements plus the ability to refer to these operands:

    - Utility functions

	Formula	
1.	Me!Height	Refer to the height of the current visual object
2.	Height	Same as formula 1
3.	Me[index+1]!Height	Refer to the height of a sibling visual object, the next object in the bundle
4.	Me[5]!Height	Refer to the height of the sixth object in the bundle.
5.	Parent!Height	Refer to the height of my parent
6.	ChildLabel!Height	Refer to the height of the first child in the bundle
7.	TaskBox!Height	Refer to the height of the first TaskBox object
8.	TaskBox[2]!Height	Refer to the height of the third TaskBox object
9.	Me.Employee.ID	Refer to ID field (of Employee table) of the current visual object
10.	Employee.ID	same as formula 9
11.	timeScale!Position(..)	Refer to the Position function provided by the first instance of a time scale

Figure 4.11: Examples of what formulas can refer to

- Properties, functions, and fields of any visual object connected to data with a different `Rows` formula.

Other property formulas can navigate to these visual objects:

- A visual object in the current bundle. The visual object can be the current or any other object in the bundle.
- A visual object in another bundle. This can be a parent, a child, or any other object in another bundle.

Once the formula navigates to a visual object, it has access to its properties, functions, or fields. In addition, Uvis formulas can refer to utility functions. Figure 4.11 gives examples of what formulas can refer to. For a complete reference on formulas, consult the Uvis reference card (40).

2. **Kinds of expressions supported:** Uvis formula expressions correspond to Visual Basic expressions. For instance, Uvis formulas support conditional, logical, string, and mathematical expressions.

3. **Utility functions:** Uvis utility functions that correspond to Visual Basic and spreadsheet functions. For instance, the regular math and aggregation functions are available.

4. **What visual objects provide:** Visual objects also provide functions the formulas can call. For instance, formulas can call the `HPosition` function of `Spiral` objects.

4.6 Limitations

Despite the expressive power of Uvis formulas, they have the limitations discussed in the following subsections.

4.6.1 Recursion and Loops

Uvis formulas alone do not support visualizations that require recursive algorithms. Such algorithms contain loops and/or functions that call themselves recursively until a condition is met.

Uvis formulas support recursion as long as it is within the context of existing visual objects. Consider the following formula:

TotalTop: `index=0 ? 0: Me[index-1]!TotalTop+Top`

The formula calculates the sum of `Top` values in a bundle of visual objects. This is an example of recursion that Uvis formulas allow. Now, let us see examples of recursion that are not possible to create.

Loops: We have a bundle of `Box`es that are connected to a table with field `Number`. We want to show the `Box`es with prime `Number`s in red. Uvis formulas alone do not support that since it requires a loop. A possible solution is to provide a utility function that checks whether a number is prime.

Inability to create visual objects recursively: Section 4.2.3 presented a two-level tree. However, Uvis formulas fall short if we want to show a recursive tree, for instance a folder tree. Since Uvis uses SQL-like formulas, it inherits SQL limitations. For instance, it is not possible to send a query that retrieves the nesting levels of the folders. As a result, it is not possible to create a recursive tree with Uvis formulas because new visual objects have to be defined for each level in the tree. A possible solution is to delegate the responsibility of constructing the recursive visual hierarchy to the visual object. Designers can set a property `Recursive` to true if they want the tree levels to be defined dynamically.

Complex Algorithms: Tree maps require a complex recursive algorithm that Uvis formulas do not support. A possible solution is to provide a visual object that performs these complex layout algorithms. Pantazos developed a `TreeMap` visual object that supports a tree map visualization with Uvis formulas (41). However, the customizability of the tree map objects becomes very limited.

Similarly, graphs of different layout types (e.g. force-directed, node-link, etc.) require complex recursive algorithms. A `Graph` visual object with a `Layout` property could support graphs of various layouts.

4.6.2 Complex Interaction

Sometimes interaction requires much more than a simple assignment statement. For instance, some interaction mechanisms such as semantic zooming are cumbersome to implement with Uvis formulas. Interactive visual objects that incorporate interaction mechanisms provide a solution. For instance, `HTimeScale` incorporates semantic zooming. When the end-user drags inwards or outwards the scale, it shows more or less time details.

Uvis provides another solution for implementing complex interaction. Developers can write `Java` or `C#` code as event handlers. However, this solution requires programming.

Sometimes visualizations should be updated constantly over a certain time period. We have not implemented a visualization that exhibits such a behaviour. However, in principle, the solution is easy. For example, Figure 4.12 shows a visualization of the annual average income and life expectancy for some countries in a certain year. The visualization is updated every 0.1 seconds. As a result, it shows the life expectancy and income for next year. When it is the year 2011, the visualization stops updating itself.

Let us see how Uvis can solve this problem in theory.

To show the current year of life expectancy and income, we defined the following properties of `YearLabel`:

Year: `init 1954`

Text: `Year`

`Year` is a designer property that retains the current year the visualization is showing information about. `Text` makes the label show the year.

Now we want to create ellipses that show country life expectancy and income for the year in `YearLabel`. To accomplish that, we defined the following formulas for `CountryEllipse`:

Rows: `Country -< Values where year=YearLabel!Year`

The `Rows` formula retrieves the information (e.g. life expectancy, income, etc.) for all countries in table `Country` provided the year is the `Year` of `YearLabel`.

To make the ellipses show information for next year every 0.1 second, we defined the following properties of the `form` object:

Timer: `YearLabel!Year < 2011 ? 0.1 : 0`

OnTimer: `YearLabel!Year = YearLabel!Year + 1, Refresh()`

The `Timer` formula looks at the `Year` property of `YearLabel`. If it is less than 2011, the time has a duration of 0.1 second. Otherwise the timer gets a zero duration. A zero duration makes the timer stop.

`OnTimer` is an event that is raised repeatedly according to the `Timer` value. When it is raised, `Year` gets increased by 1, and the visualization is updated.

At present Uvis does not have a timer, but the plan is to make one similar to what for instance MS Access has: A timer in each `Form` object. With this in place, an animation could be made as we discussed.

4.6.3 Other Types of Visualizations

Despite their importance, we have not implemented some types of visualizations such as geographical ones. A possible solution to geographical visualizations is to provide a `Map` visual object that can show a geographical map, and translate coordinates to pixel positions.

4.6.4 Inability to Define Functions

A designer can not define new functions in Uvis. They require programming, however. An escape solution is to provide utility functions or specialized visual objects that perform the required functionality.

4.7 Summary

Despite the limitations, it is possible to create lots of custom visualizations with Uvis.

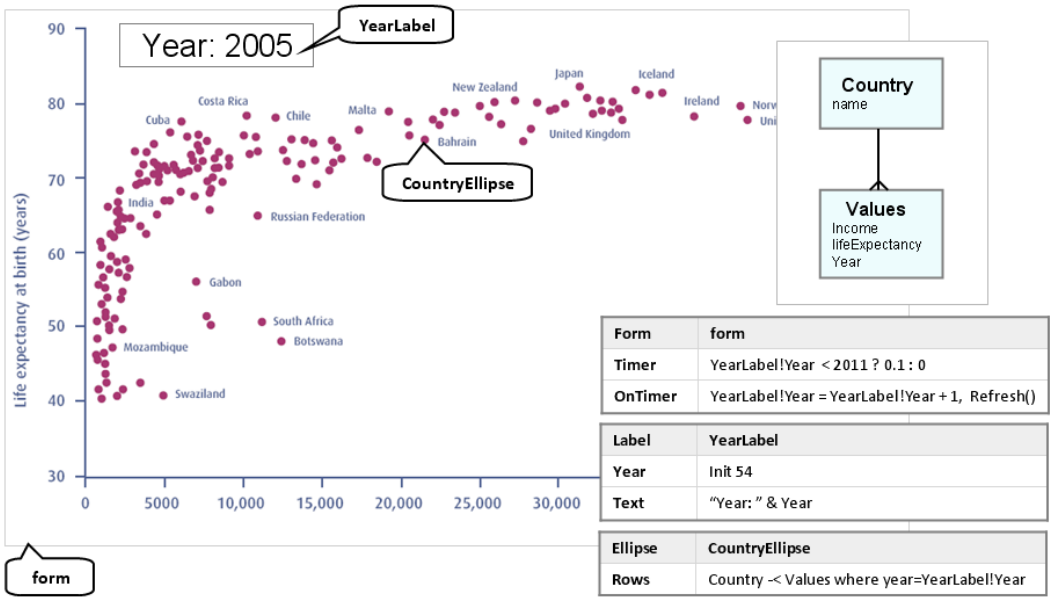


Figure 4.12: A visualization that is updated every 0.1 seconds. The visualization is adapted from (2)

Whenever it is not possible or cumbersome to create a visualization, a third party can provide a specialized object that makes it easy and possible. For instance, it is not possible to create a spiral with Uvis formulas and `Splines`. This requires a recursive algorithm. Hence, we provide a `Spiral` specialized object (section 4.2.4.). It is cumbersome to create an indented tree with primitives (e.g. line, label, etc.). Thus, we provide a `TreeNode` specialized object (section 4.2.3.)

Specialized objects reduce customizability, but are convenient to use. Other visualization tools such as Protovis use a similar approach. For instance, some visual objects have a `Layout` property that automatically positions them. However, unlike Protovis' program-like specifications, Uvis uses spreadsheet-like formulas also in these cases.

5

Uvis Usability

5.1 Introduction

For many reasons, it can be challenging to implement or refine custom visualizations like the ones in Chapters 3 and 4. For instance, some formula concepts are new to designers or it is hard to verify that the implemented visualizations are correct. Being aware of that, the original Uvis approach uses a development environment that provides cognitive support for designers. For instance, the environment highlights the problematic parts of the formulas, and immediately updates the visualization.

I made several usability studies with savvy designers to find usability problems in the initial approach. The details of the studies are presented in chapter 6. The studies resulted in new features in the environment to improve usability. Further, I investigated other ways of making Uvis easy to learn. For instance, I designed visual objects with default formulas that cater for common cases. Further, I provided a tutorial that thoroughly explains the concepts to the designers.

This chapter presents the principles behind the initial and enhanced versions of the Uvis system.

5.2 Initial Uvis Version

This section presents the main principles behind the initial Uvis version. The principles aim at providing a system that is easy to use. Let us look at the details.

5.2.1 Drag-Drop-Set-Property

Existing tools for constructing user screens (e.g. MS Visual Studio) use the *drag-drop-set-property* principle. The developer drops components (buttons, text boxes, etc.) on the screen and defines their properties (e.g. position, colour and text.) Then the screen looks right, but it has little functionality. If developers want real functionality or a custom visualization, they have to switch to tools that are more like programming. An evaluation study (11) gave an overview of user interface tools in 2000 and explained why drag-drop-set-property tools were much more successful with designers than program-based tools.

Uvis uses the existing drag-drop-set-property principle, but allows designers to implement custom visualizations that show data as position, colour, etc., and respond to events.

The basic version of Uvis consists of seven panels (Figure 5.1) : Toolbox, property grid, property values, visualization form, data model, error list, and application folder. The *toolbox* is a list of the available visual objects. The *property grid* shows the property formulas that define/set the appearance of the visual objects. The *property values* shows the property values of an individual selected visual object. The *visualization form* is the visualization the designer builds. The *data model* is the structure of the data that the designer has access to. The *error list* shows the problems with the visualization specifications. The *application form* displays the directory of the current Uvis application.

To build a visualization, designers drag a visual object from the toolbox and drop it on the visualization form. They can set the properties of the visual object using the property grid. The changes are reflected immediately on the visualization form. If designers want to see the property values of an individual visual object, they can select an object (using ctrl+click) and view the properties in the property values panel.

5.2.2 Documentation

The initial documentation for designers was a seven-page tutorial. The tutorial consists of text and figures that are in separate pages (Figure 5.2). The text has a two-column style. The tutorial explained step-wise how to create a custom visualization. Uvis concepts are explained meanwhile. The objective of each step is clearly stated.

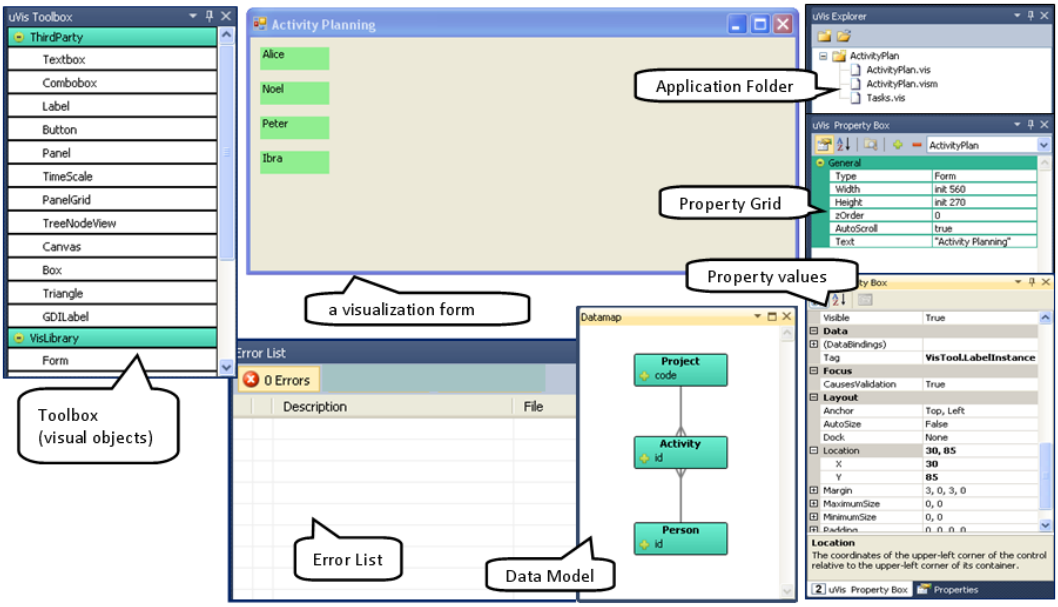


Figure 5.1: Basic version of Uvis environment

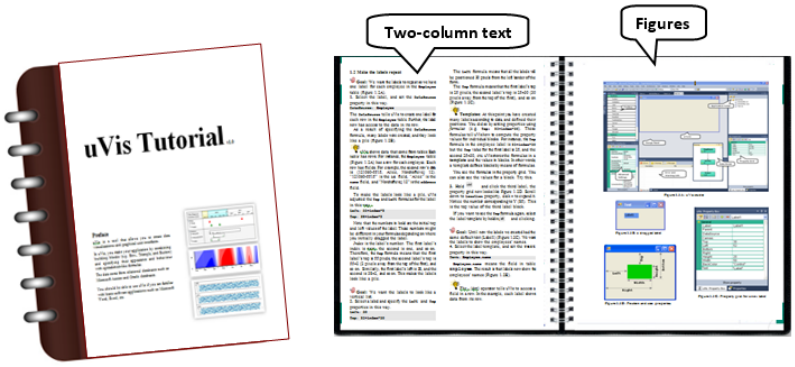


Figure 5.2: Uvis tutorial, version 1

5.2.3 Only Visual Objects

Unlike present tools that use invisible objects that can be used to draw something visual on the screen, Uvis visual objects are *visual* as the name implies. They can be seen on the screen immediately when the designer drags and drops them. Visibility improves usability since it keeps designers informed about what is going on (42).

5.3 Uvis Enhanced Version

The Uvis enhanced version is a result of several usability studies with savvy designers (Figure 5.3). Chapter 6 provides the details. This section only explains the enhanced version.

The enhanced version kept the parts that communicated well with the designers such as property grid, data model, etc. However, other parts such as the property values panel confused the designers. Therefore, they were removed.

The designers needed more cognitive aids to learn how to create or modify custom visualizations. The new cognitive aids helped removing many usability problems.

The following sub-sections present these cognitive aids.

5.3.1 Table view

Table view shows a sample of the data table on demand. To view a table sample, the designer clicks a table box in the data model. This feature helps designers explore the data they want to visualize. Such exploration helps them make sense of data particularly if the data field names are not self descriptive. For instance, the designer clicked the *Employee* box in the data model. As a result, a sample of the `Employee` table showed up. The field `weeklyHours` means the hours the employees work per week. It might not be descriptive for some, but looking at the values can give hints about what it means. A research study showed that novice designers relate to data using concrete values rather than field names (43).

Designers can also explore the data to be aware of irregular data values (typos, null values, etc.)

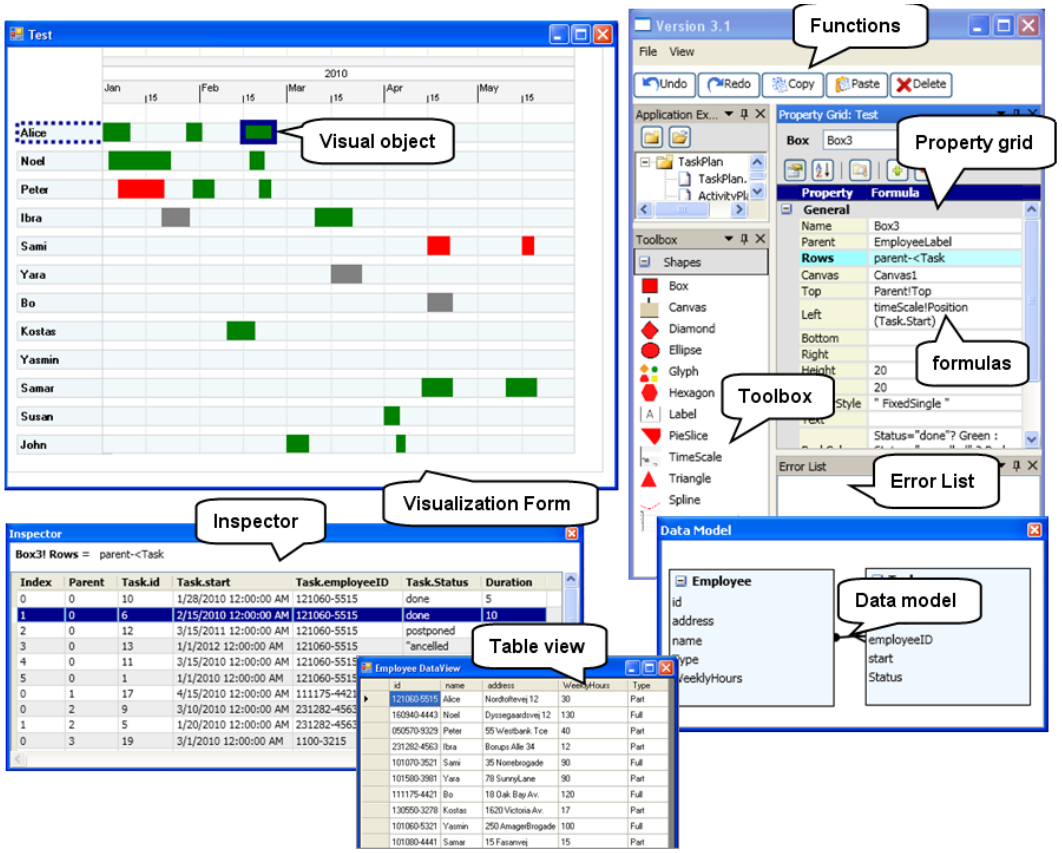


Figure 5.3: Enhanced version of Uvis environment

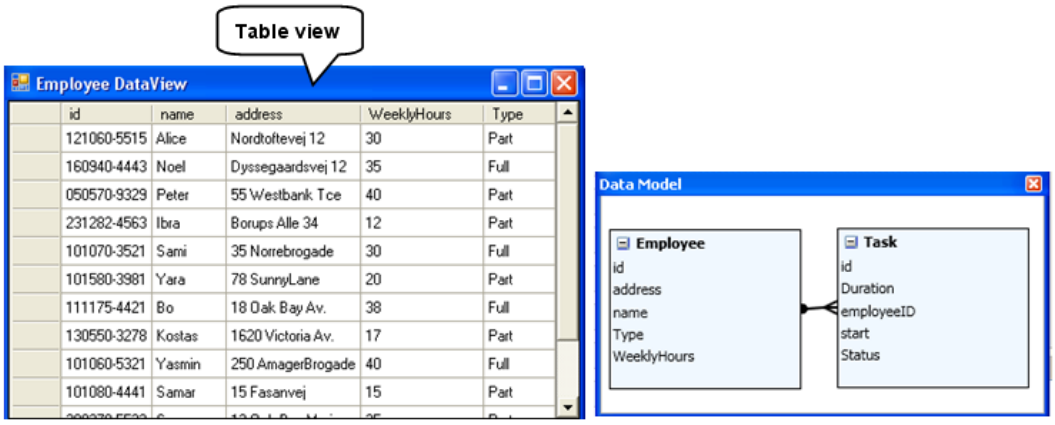


Figure 5.4: The table view feature

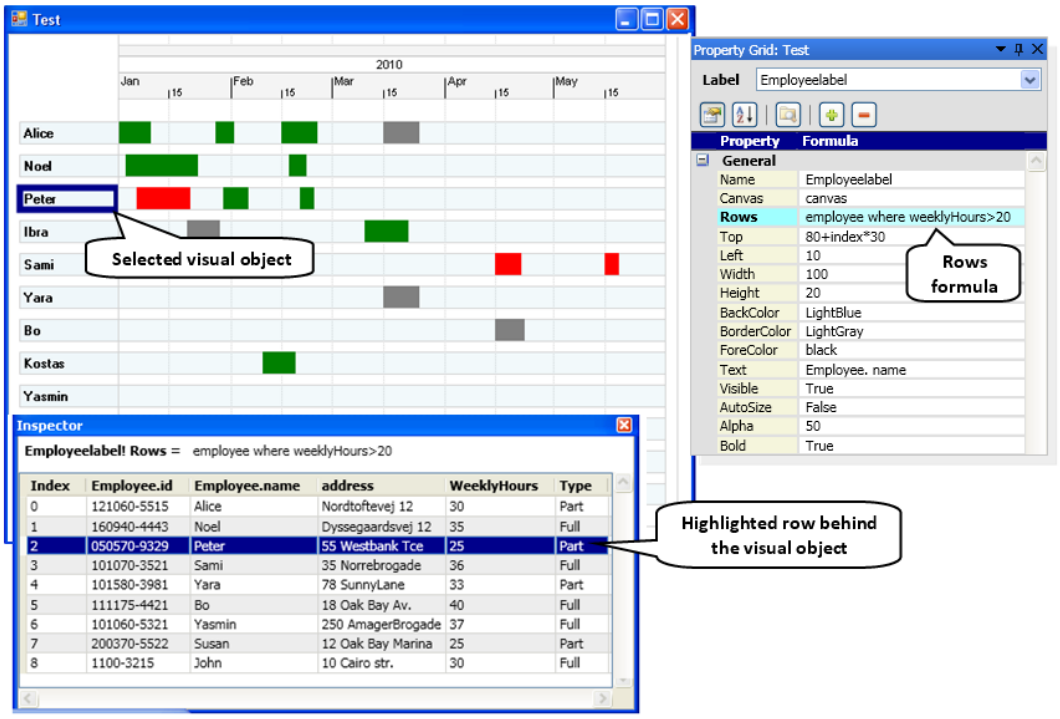


Figure 5.5: The inspector showing the relationship between a visual object and a data row

5.3.2 Inspector

The usability studies revealed that designers encountered difficulties with visual mappings. Particularly, understanding the relationship between visual objects and data. Other research studies showed that novice designers experienced similar problems with visual mappings ((44), (43).)

In response, I developed the *inspector*, a data grid that shows the data behind visual objects and properties. Let us look at the details.

- **Connection Between Visual Objects and Data:** Figure 5.5 shows the task map visualization (presented in chapter 3) in Uvis environment. Three parts of the environment are shown: The visualization, the property grid, and the inspector.

  The designer selected (clicked) a label showing employee Peter. The inspector highlighted the data row behind the label. According to the formula that connects the labels to data (`Rows` property), only employees who work more than 20 hours

per week should be shown. To confirm that the expression is correct, the designer can sort (click) the `WeeklyHours` field in the inspector to check if there are values less than 20.

Principle: The inspector allows the designers to view the relationship between a visual object and the underlying data. Selection can be done both ways. Designers can select rows in the inspector and the corresponding visual objects are highlighted and vice versa. When the underlying data changes (due to a change in the `Rows` formula), the data in the inspector is updated immediately.

- **Connection Between Visual Properties and Data:** Figure 5.6 shows that the designer has selected (clicked) a `Box` (`TaskBox`) representing Alice's task on 28th January 2010 and the `Left` property that positions the boxes according to the time scale.

  The `Left` property of the `TaskBox` visual object is defined by an expression (`timeScale!Position(Task.Start)`).

  The inspector breaks the expression down into two sub-expressions: `Task.Start` and `timescale!Position(Task.Start)`, and shows the values of the sub-expressions as well as the index of each `TaskBox` object in the bundle.

  Principle: The inspector allows the designer to view the details of the visual property mappings and the data behind them. This has a potential of improving the designer's understanding of how visual mappings show data.

- **Problematic Data Values:** Figure 5.7 shows ellipses representing charity marathon runners. The size of the ellipses represent the runners age. The `Left` formula results in negative values for the first two objects. As a result, the objects could be fully or partly out of view. Hence, the inspector shows the values in yellow as a warning. If the designer did not intend for this to happen, a visual feedback would not help. Only concrete values can reveal such a problem. The `Hight` and `Width` formulas are identical, and they refer to field `Age`. For runner Laura, the value is null. The default values for `Hight` and `Width` in this case are 0, but the inspector shows the null value in red so the designer is aware.

  Principle: In the world of programming, values such as null and division by zero can be problematic. This applies to the visualization world too, and the

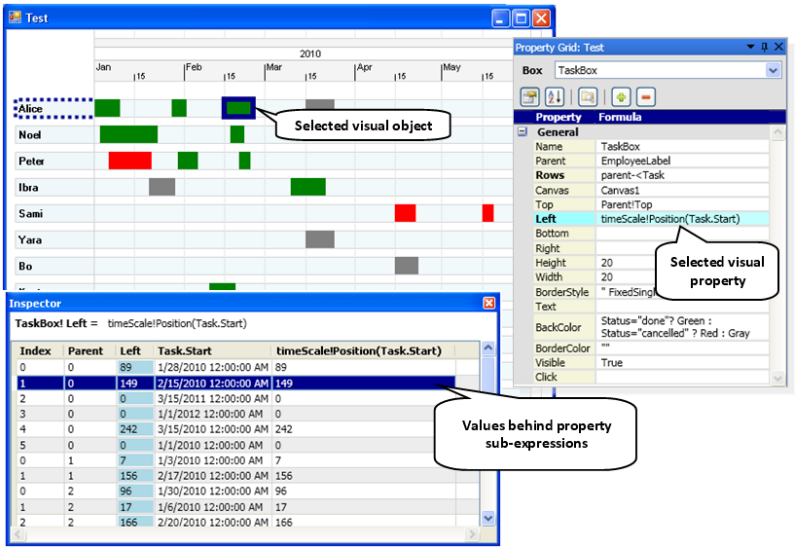


Figure 5.6: The inspector showing values behind the formula sub-expressions

inspector highlights these values in light red (erroneous values). The values that could cause visual objects to be out of view or invisible such as negative values for position and size properties are taken into consideration. These values are highlighted in yellow (warning).

5.3.3 Showing multiple visual objects as a staircase

Connecting a visual object to data through `Rows` formulas results in multiple objects. When the designer typed a Rows formula, the multiple visual objects were on top of each other visually. They looked like a single object, and the designer was puzzled. A visual feedback was missing.

To give the designers visual feedback, Uvis sets `Top` and `Left` formulas for the visual object when the designer types a `Rows` formula. The result is that the visual objects cascade like a staircase (Figure 5.8). This helps the designer learn that multiple visual objects are created as a result of connecting them to data.

This effect works only if `Top` and `Left` values are constants, for instance, the designer has just dragged and dropped a visual object. However, if `Top` or `Left` has a formula, Uvis does not change it since it would be changing a designer's specification.

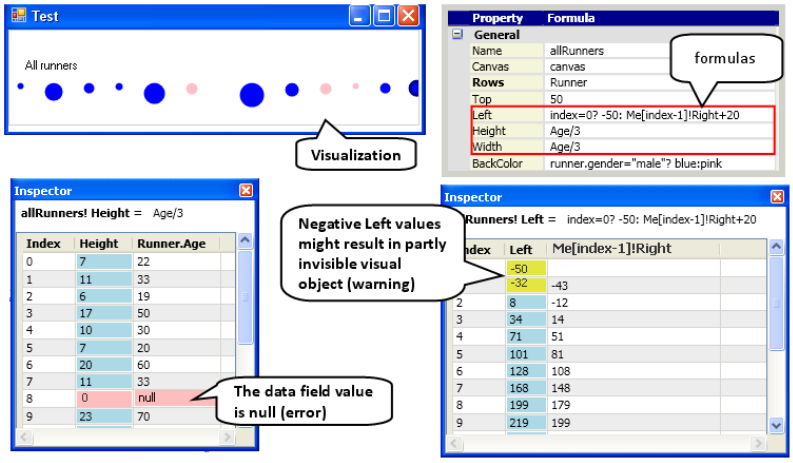


Figure 5.7: The inspector showing irregular values in red and warnings in yellow

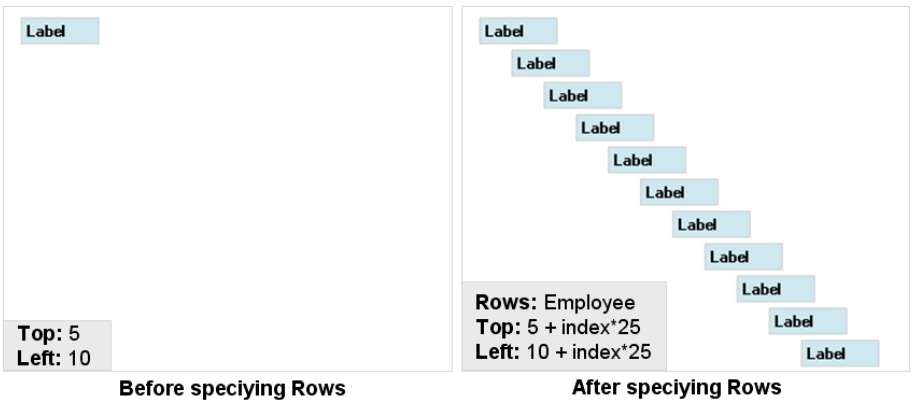


Figure 5.8: The staircase metaphor

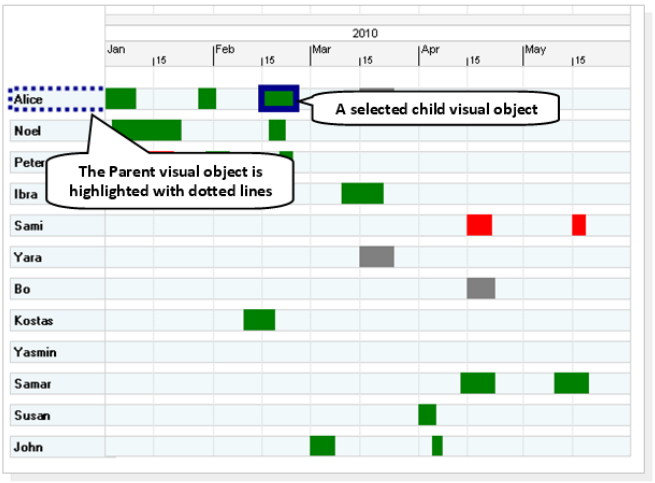


Figure 5.9: Highlighting parent visual objects

5.3.4 Showing Parent

It was hard for some designers to learn the `Parent` concept. To help designers identify parent visual objects, Uvis environment highlights parent visual objects in a dotted frame (Figure 5.9).

5.3.5 Positioning children on top of parents

To help designers understand that a child object is created per parent object (provided the child has no `Rows` formula), Uvis positions the child objects on top of parent objects. For instance, Figure 5.10 shows that Uvis positioned the `TaskTriangle`s on top of `EmployeeLabel`s by changing the `Top` and `Left` formulas. Again, only constant formulas are changed.

Rather than setting `Top` and `Left` properties, `PieSlice` objects are positioned using properties such as `CenterX`, `CenterY`, etc. Figure 5.11 shows an example.

5.3.6 Visual Editing Functions

A common feature in drawing tools is to allow designers to copy, cut, paste, and delete text or visual objects for efficiency or ease of reuse. Naturally some designers missed these functionalities and tried to copy and paste some visual objects without success. As a result, the enhanced environment introduced editing features.This introduced some

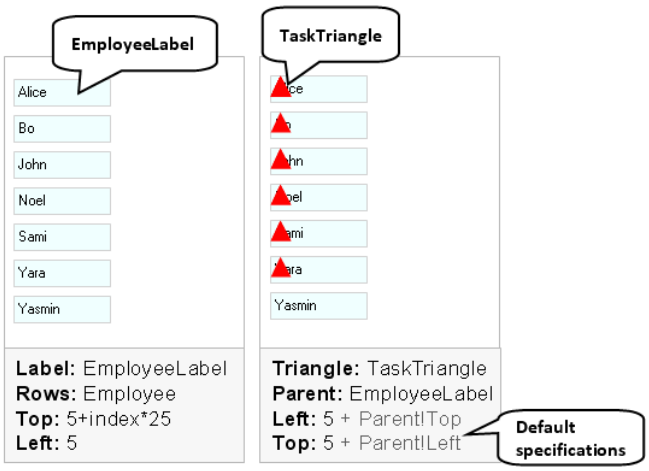


Figure 5.10: Positioning child objects on top of parent objects

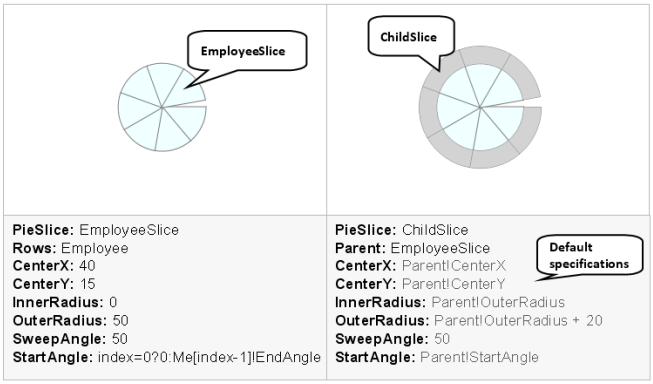


Figure 5.11: Positioning `PieSlice` child objects on top of parent objects

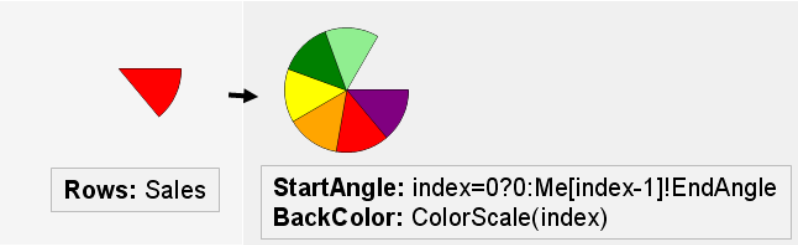


Figure 5.12: Setting the pie slice's StartAngle

difficulties though. Position formulas of the newly copied objects have to be adjusted so that the copied object is not on top of the source object. It has to be horizontally and vertically shifted.

5.3.7 Default Formulas

To improve ease of use without compromising customizability, some visual objects provide default formulas that cater for common cases. These formulas are still changeable by the designers if they want a different behaviour. As an example, the `StartAngle` of a `PieSlice` object has a default formula (Figure 5.12). As another example, `HTimeScale` has a default formula that calls `Refresh()` when the event `Dragged` is triggered. Chapter 4 has more examples.

5.3.8 Documentation

The documentation is divided into two parts. A step-wise tutorial, and visualization examples.

- **Tutorial:** The textual tutorial did not communicate all the Uvis concepts effectively. Designers skipped some parts or did not fully relate the text to the environment parts. Moreover, designers felt awkward about steps that asked them to carry out unfulfilling tasks, for instance, steps that did not have a real impact or output. These steps were present because they were important for the concept.

  As a solution, I designed a power-point based tutorial (Figure 5.13). The tutorial showed information bit by bit to increase the chances of designers not skipping

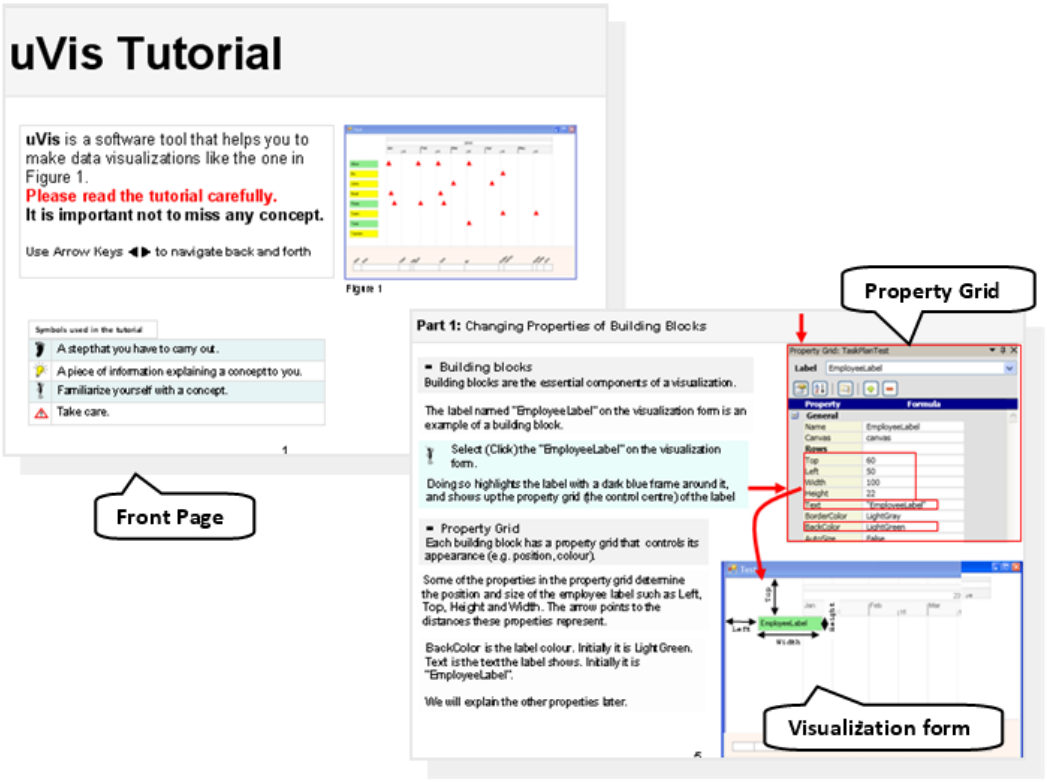


Figure 5.13: A power-point based tutorial

parts. Furthermore, the steps were only the tasks that resulted in something real on the screen.

The tutorial was improved in other areas too. For instance, the language was simplified to correspond to the designer's language, the slides were consistent, and smooth animation was used to draw the attention of the designer to new concepts.

- **Visualization examples:** It is well known that concrete examples improve understanding (45). This was supported with evidence from usability studies too. Designers missed an example that is similar to some tasks. In response, examples on pie slices and curves were produced

5.3.9 Benefits

Although the improvements of Uvis were based on feedback from savvy designers, it is hard to tell the precise impact of individual improvements on ease of learning. The improvements collectively reduced the usability problems that designers encountered with the initial version of Uvis. Chapter 6 provides more details. In one case, however, I tested the impact of a major cognitive aid as explained in chapter 7. The result is that it improved completion time and solution quality.

6

Iterative Design of the Uvis System

6.1 Introduction

The main objective of the Uvis system (language, environment, visual objects, and tutorial) is to make custom visualizations accessible to savvy designers. The initial version of the Uvis system in chapter 5 was not tested with designers. This chapter presents how the Uvis system evolved iteratively through involving novice, savvy, and expert designers. The iterative design process was followed to refine the Uvis system.

This chapter is structured as follows: First, it briefly explains the iterative design process, the objectives of using the process, the Uvis concepts to be evaluated, and the tasks designed to evaluate them. Second, the chapter presents the rounds that the Uvis system went through. Finally, a summary of the findings is given.

6.2 Iterative Design Process

It has been widely recognized that a user interface (UI) should be designed iteratively since it is almost impossible to design a UI without a usability problem from the beginning (46, 47, 48). Iterative design (Figure 6.1) is a cyclic process of prototyping, testing, and refining a UI. An initial prototype is proposed first. The prototype is usability tested with typical users. Usability studies identify usability problems. The problems are dealt with according to their severity, and ease of fixing(49). As a result,

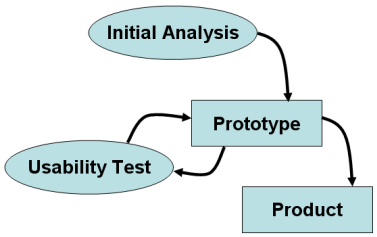


Figure 6.1: The iterative design process

a new prototype might be designed and usability tested. The usability test can be modified too, and so on until a stable version is reached.

The following subsections present the objectives of using the iterative design process, and the Uvis concepts that the process is designed to evaluate and make accessible to designers.

6.2.1 Objectives

- Evaluating how easy it is to learn and/or understand Uvis main concepts, and use Uvis.
- Making custom visualizations accessible to designers based on feedback from usability studies.
- Investigating new ways to support designers.

6.2.2 Uvis Concepts to Evaluate

Figures 6.2 and 6.3 provide overviews of selected Uvis language, environment, and visual object concepts to evaluate. Only concepts crucial for using Uvis are selected. For each concept, there are one or more usability factors (e.g. ease of learning) used to evaluate. For instance, an ease of learning factor means evaluating how easy it is to learn a concept. Further, each concept is classified according to where it belongs in the data transformations and/or visual mappings steps (two steps in the visualization reference model (50))

The usability studies in section 6.4 will explain how I evaluate the Uvis concepts and measure the corresponding usability factors.

Uvis Concept	Factor		Process	
	Ease of learning	Understandability	Data Transformations	Visual Mappings
1. Uvis Language				
1.1. Visual objects and data The Rows formula retries a record set, and create a visual object for each row in the record set.	✓	✓		✓
1.2. Filter a Table Writing a simple where expression	✓		✓	
1.3. Sort a Table Sorting a table by a column	✓		✓	
1.4. Join Two Tables Writing a simple join expression	✓		✓	
1.5. Visual objects and properties:				
1.5.1. Index-based position formula How Uvis evaluates position formulas that contain an index for each visual object in a bundle	✓			✓
1.5.2. Data field formulas How Uvis evaluates formulas that refer to data fields.	✓			✓
1.5.3. Visual property formulas How Uvis evaluates formulas that refer to visual properties	✓			✓
1.5.4. Parent property formulas How Uvis evaluates formulas that refer to visual properties or fields of parents	✓			✓

Figure 6.2: Uvis language concepts

Uvis Concept	Factor		Process	
	Ease of learning	Understandability	Data Transformations	Visual Mappings
2. Uvis Environment				
2.1. Immediate visual feedback Updating the visualization immediately based on setting the properties of visual objects.	✓		✓	✓
2.2. Drag-Drop Dragging a visual object and dropping it on the design panel	✓			✓
2.3. Property Grid				
2.3.1. Visual objects and the property grid Showing the properties of the selected visual object in the property grid.	✓		✓	✓
2.3.2. Setting properties Setting the properties in the property grid.	✓		✓	✓
2.4. Data Model				
2.4.1. Understanding the data model		✓	✓	✓
2.4.2 Using the data model	✓		✓	✓
2.5. Error Highlighting Acting upon error highlighting	✓	✓	✓	✓
2.6. Table View Using the table view feature	✓		✓	✓
2.7. Inspector Using and understanding the inspector	✓	✓	✓	✓
3. Visual Objects				
3.1. Primitive objects				
3.1.1. Position properties Using position properties (i.e. Top and Left)	✓			✓
3.2.1 Size properties Using size (i.e. Height and Width)	✓			✓
3.2.2 Colour properties Using colour properties (e.g. BackColor)	✓			✓
3.2. Specialized objects Using a specialized object	✓			✓

Figure 6.3: Uvis environment and visual object concepts

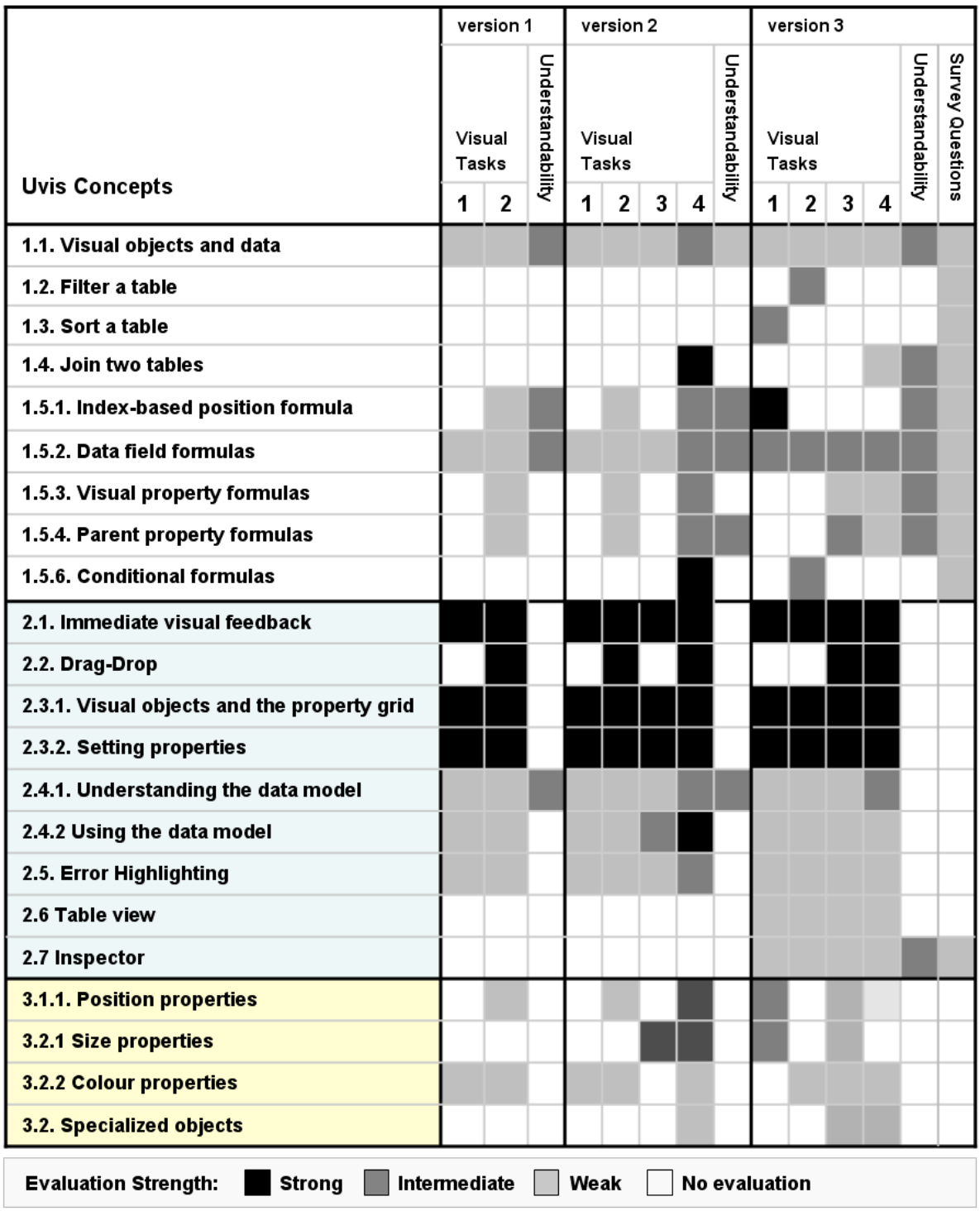


Figure 6.4: The Uvis concepts that tasks evaluate

6.3 Test Tasks

This section presents different versions of test tasks. The tasks are designed to evaluate the Uvis concepts. Participants carry out the tasks during the usability studies. Together with Uvis, the tasks iteratively evolved as it was feasible to test more concepts.

The tasks can be visual, understandability questions, or survey questions. The *visual tasks* are tasks that ask the participant to create or refine a visualization. *Understandability questions* ask participants questions to check their understanding. *Survey Questions* check the participant's opinions on Uvis concepts and collect information about the participant's experience.

For visual tasks, participants saw the goal that they should accomplish on the screen. For instance, they saw an example of how the goal visualization should look. The data sets in the participant tasks were different from the ones shown to them. They were told that the visualizations shown to them in the task are just examples.

The tasks were designed to fulfil three criteria: First, the visual tasks should cover a collection of different custom visualizations. Second, all the tasks (e.g. visual, understanding, etc.) should evaluate Uvis concepts in figures 6.2 and 6.3. Third, all the tasks should vary in complexity. Fourth, Together with the usability studies, the tasks should not take longer than two hours.

As the tasks evolved, they fulfilled the criteria.

Figure 6.4 shows how the different task versions evolved to evaluate more concepts.

6.3.1 First Version of Tasks

Figure 6.5 shows the first version of the visual tasks. The visual tasks and understandability questions evaluate fundamental formula concepts such as how formulas bind visual objects to data rows. The evaluation is not strong since there were only two simple tasks that demonstrate very little of the formula power (Figure 6.4).

The tasks also evaluate basic features of the environment such as the drag-drop and the immediate visual feedback concept.

- **Visual Tasks:**
  - **Task 1:** The vertical list shows employee names. Make the list show their addresses instead.

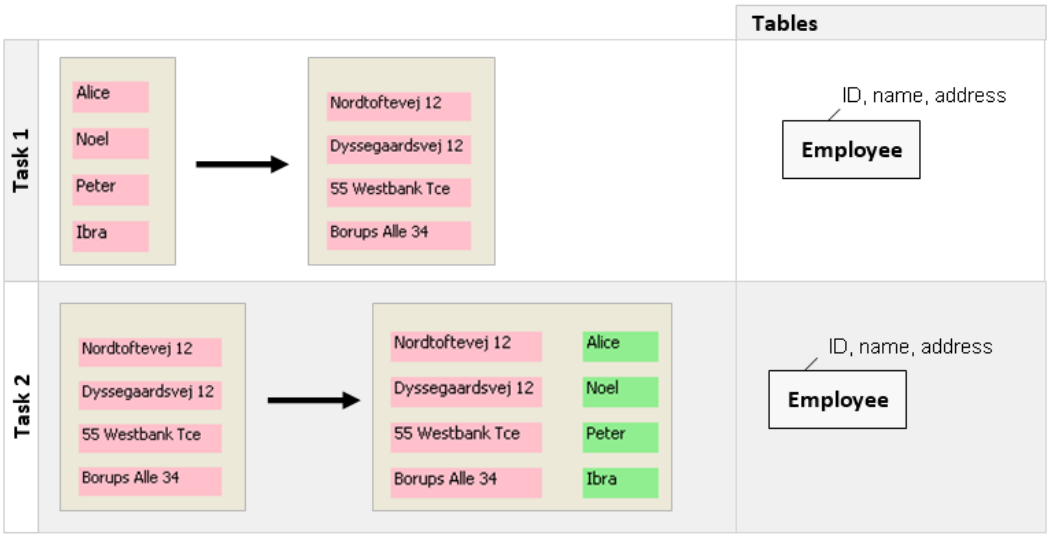


Figure 6.5: Visual tasks, version 1

Data: Table `Employee`.

– **Task 2:** Show employee names in light green, and position the names to the right of their addresses.

Data: Table `Employee`.

- **Understandability Questions:**

  – **Question 1:** What data do the employee labels in Task 1 show? Where do the data come from?

  – **Question 2:** Can you explain how the employee labels in Task 1 are positioned like a vertical list?

6.3.2 Second Version of Tasks

Figure 6.6 shows the second version of the visual tasks. This version of tasks and understandability questions evaluate more advanced formula concepts than the first version. For instance, the tasks evaluate join formulas, conditional formulas, and formulas that refer to visual properties.

This version of tasks evaluates some development environment concepts stronger than the first version. For instance, the data model concept is strongly evaluated in task 4 since designers have to work out a problem from scratch. They actually have to use the data model extensively.

The visual tasks vary in complexity. For instance, some tasks draw on concepts that are familiar to spreadsheet users (e.g. basic mathematical formulas) while others require the understanding of Uvis specific formulas

- **Visual Tasks:**
  - **Task 1:** The pink vertical list shows employee names. Make the list show their addresses instead, also change the list colour to yellow.

    Data: Table `Employee`.
  - **Task 2:** Show employee names in light green, and position them to the right of their addresses.

    Data: Table `Employee`.
  - **Task 3:** The visualization shows the employee activities in a certain period of time. Make the activity width represent the activity duration.

    Data: Tables `Employee` and `Activity`. One employee can have zero or more activities.
  - **Task 4:** Create a visualization that shows the projects and their activities. The activities are positioned according to the time scale, and the projects they belong to.

    Data: Tables `Project` and `Activity`. One project can have zero or more activities.
- **Understandability Questions:**

- **Question 1:** What data are the employee labels in Task 1 showing? Where do the data come from?
- **Question 2:** Can you explain how the employee labels in Task 1 are positioned like a vertical list?
- **Question 3:** Can you explain what `Parent` means?
- **Question 3:** Can you explain what the join (`-<`) symbol mean?

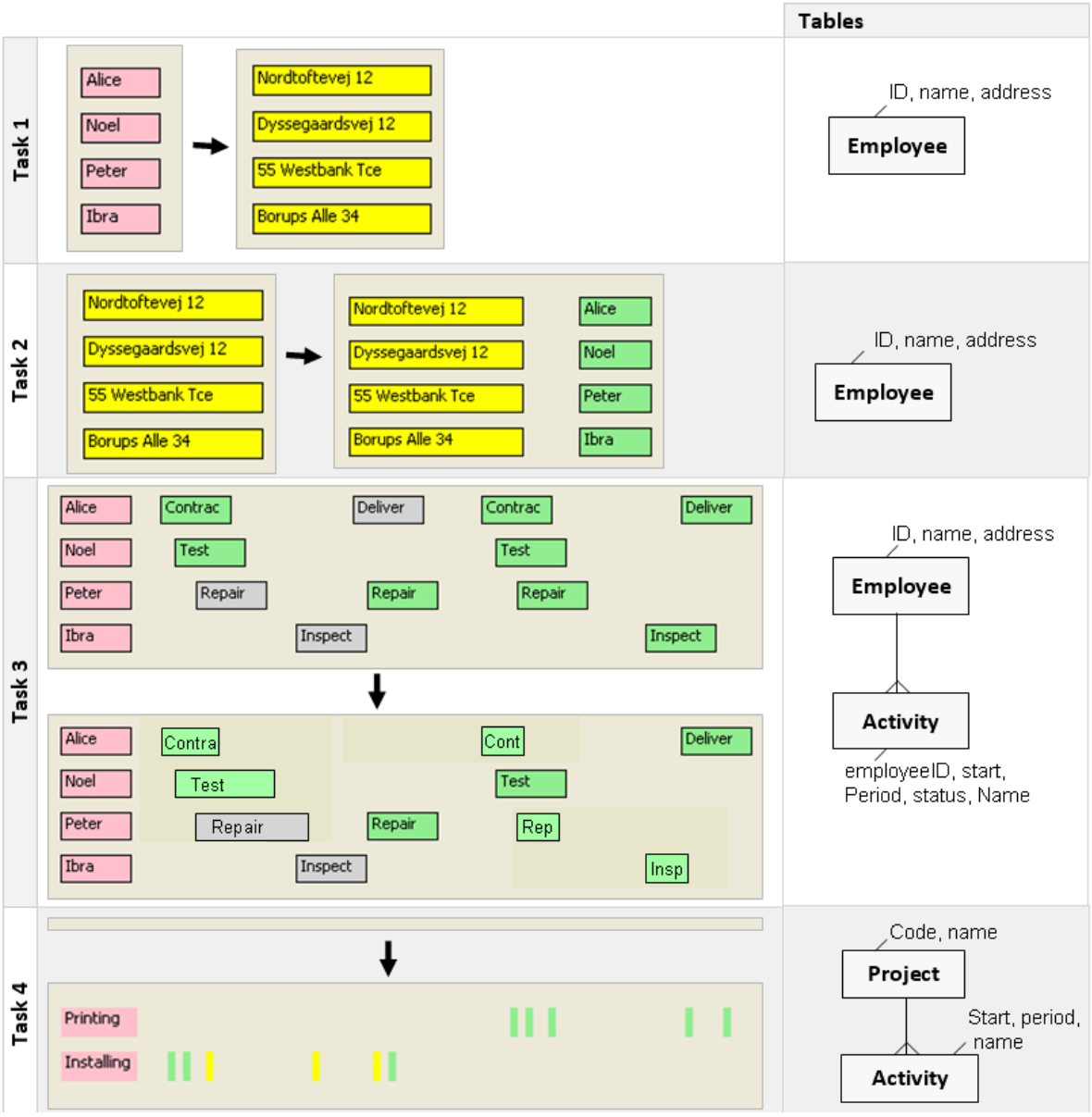


Figure 6.6: Visual tasks, version 2

6.3.3 Third Version of Tasks

Figure 6.7 shows the third version of the visual tasks. The visual tasks evaluate all the Uvis concepts. Some concepts (e.g. joining two tables) are not evaluated strongly by the visual tasks, but the understandability questions and opinion survey provide a supplement to that.

The visual tasks progress in complexity from easy to difficult.

- **Visual Tasks:**
  - **Task 1:** The bars show data from table `Sales`.
    - **A.** Position the bars horizontally.
    - **B.** Make the bar heights show the amount of sales.
    - **C.** Sort the bars according to the amount of sales.

    Data: Table `Sales`.
  - **Task 2:**
    - **A.** The ellipses on top (grey ellipses) show all runners of a marathon. Make the male runners blue, and the female ones pink.
    - **B.** On the bottom (the Citizen runners row): The ellipses show runners that are citizens. Now we want the ellipses to only show runners that are older than 30. Also, change the label from "Citizen runners" into "Runners older than 30".
  - **Task 3:** You have a custom pie chart (see figure below) representing percentages of all passengers of several flying classes (e.g. Crew, Economy, etc.). The percentages of male passengers are shown in light blue pie slices.

    Add pink pie slices that show percentages of female passengers on the top of the male passengers.

    Data: Table `Passenger`
  - **Task 4:** The visualization shows the high temperature readings in three cities in the period of time from 1 June 2011 to 1 October 2011. The cities are shown by the labels on the left. The time is displayed by a time scale on the top. Numeric scales on the right show the range of possible temperatures in Celsius. The high temperature readings are shown as red curves.

Add blue curves showing low temperature reading for the shown cities.

Data: Tables `City`, `HighReading`, and `LowReading`. One city can have zero or more high readings/low readings.

- **Survey Questions:**
  - To what extent do you agree with the following statements?

    The answer should be: I strongly agree, I agree, I neither disagree nor agree, I disagree, or I strongly disagree.
    - I am confident that my visualizations produce the expected outcomes described in the tasks
    - The inspector was helpful.
    - The tutorial was helpful.
    - The formulas were easy to understand.
  - How often did you use the inspector on average per task?
  - What difficulties did you encounter during the study?
  - Which parts of the formulas were difficult to understand for you?
  - Which parts of the formulas were easy to understand for you?
  - Do you have any suggestions for improvement?
- **Understandability Questions:**
  - Describe the effect of the "." element in the Uvis formulas.
  - Describe the effect of the "!" element in the Uvis formulas.
  - Describe the effect of the `"-<"` element in the Uvis formulas
  - Describe the effect of the "index" element in the Uvis formulas.

The following subsections will present the phases that the Uvis system went through. In each phase, the section gives a summary of one ore more usability studies and the identified problems and their fixes. At the end of each phase, a new version is presented, and the refinements are explained.

The details of the usability studies can be found at (51).

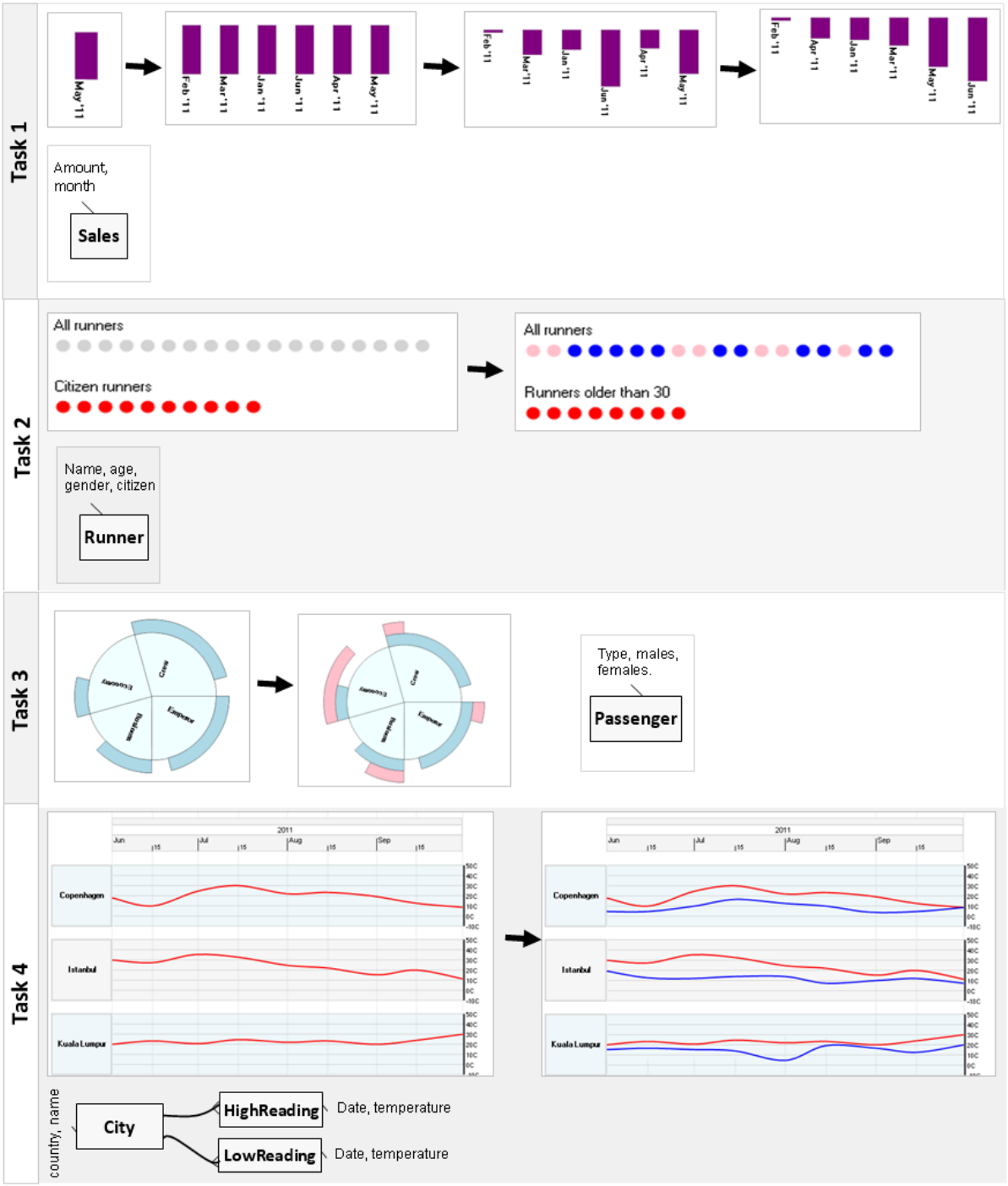


Figure 6.7: Visual tasks, version 3

6.4 First Phase of Evaluation

This phase was carried out with one participant only. One participant is enough to detect usability problems that everyone will encounter.

6.4.1 The Participant's Background

- **Participant 1**
  - **Gender:** male
  - **Age:** 29
  - **Position:** medicine student.
  - **IT skills:** novice IT user, has basic knowledge of MS word and power-point.

6.4.2 The Usability Study Settings

- **Tutorial:** The first version of the Uvis tutorial, a textual tutorial that explains step-wise how to make a custom visualization (Employee activity plan). The tutorial has a two-column style, and the figures are in separate pages.
- **Uvis environment:** The first version of the Uvis environment, the initial version of the environment that is presented in chapter 5.
- **Test duration:** 1 hour and 30 minutes.
- **Procedure:** The test was carried out in a lab. The participant was asked to read the tutorial, follow the steps he is asked to do, and think aloud meanwhile. The tutorial had two sections. At the end of each section, the participant was asked to carry out a task and answer a few understandability questions.
- **Visual Tasks:** Tasks 1 and 2, version 1 (Figure 6.5).
- **Understandability Questions:** Questions 1 and 2, version 1.

6.4.3 Qualitative Results:

The participant could easily learn some concepts of the Uvis system. For instance, the immediate visual feedback and how to set a property and a few other concepts seemed natural. However, he could not answer the questions.

The participant encountered these problems.

- **Problem 1: Connection between visual objects and table rows:** When asked about the relationship between visual objects and data, the participant could not explain that each visual block is bound to a data row. "It comes from the table somehow", he said.
- **Problem 2: Data field formulas:** The participant thought he needed to type the field value for each label's text (Task 1).
- **Problem 3: Data Model:** The participant could not use the data model in both tasks. He did look at it, but could not see the connection between the data model, and what he needed to do (Tasks 1 and 2).
- **Problem 4: Index-based position formulas:** The participant could not figure out how index-based position formulas (i.e. vertical list) were calculated (Question 2).
- **Problem 5: Selecting visual objects is cumbersome:** At times, the participant forgot how to select a visual object. It was cumbersome to remember the combination of ctrl and click.

6.4.4 Quantitative results:

The participant failed in both visual tasks. He spent 15 minutes on task 1 and 20 minutes on task 2.

6.4.5 Causes and Solutions:

Figure 6.8 provides an overview of the problems, causes, and solutions.

- **Cause 1: Insufficient explanation:** Some Uvis concepts (e.g. visual objects and data, etc.) were not explained well in the tutorial. The language was rather

Problems
1. Connection between visual objects and table rows
2. Data field formulas
3. Using and understanding the Data Model
4. Index-based position formulas
5. Selecting visual objects is cumbersome

Causes	Problems					Solutions
	1	2	3	4	5	
1. Insufficient explanation	✓	✓	✓	✓		• Provide better explanation
2. No table view	✓	✓	✓			• Show the tables upfront in the tutorial.
3. Poor property value view	✓	✓		✓		• Provide a third column in the property grid that show property value.
4. The pile of labels did not communicate	✓					• Make the label borders visible. • Displace the labels further
5. Ctrl+ Click is cumbersome					✓	• Select objects using Click only

Figure 6.8: The first phase problems, causes, and solutions

technical. Furthermore, the tutorial layout was not intuitive to the participant. This was judged to be a reason behind the four problems the participant encountered.

Solution: Avoid technical language. Switch to a regular layout (i.e. one column, pictures and text go hand in hand), Emphasize the concepts that were problematic.

- **Cause 2: No table view:** It was hard to imagine that there were data rows behind the visual objects simply because the participant could not see the data rows. This was judged to be a reason behind problems 1, 2, and 3.

  Solution: Simply show the tables upfront (`Employee` and `Activity`) in the tutorial.

- **Cause 3: Poor property value view:** The participant could not understand the property value panel. It looked so different from the property grid. This was judged to be a reason behind problems 1, 2, and 4.

Solution: Add a third column in the property grid. This column shows the values of the properties for a selected visual object.

- **Cause 4: The pile of labels did not communicate:** Upon defining a `Rows` formula, Uvis sets the `Top` and `Left` formulas automatically. This causes the labels to cascade a bit, but the labels did not have visible borders. The participant could not correctly interpret this cognitive aid. "It just looked a bit bigger", he said. This was judged to be a reason behind problems 1.

  Solution: Make the label borders visible. Displace the labels further

- **Cause 4: Ctrl+ click is cumbersome:** Selecting a visual object this way is unusual. It was decided to simply allow selecting a visual object by simply clicking it.

6.4.6 Changes - the second version of Uvis

Development Environment: The second version of the Uvis environment was implemented as a result of the study. Figure 6.9 shows the changes in the environment. A third column that shows property values was added. When the designer clicks a visual object, the property values of the object are shown in the column in grey colour. Moreover, the pile of labels is now more visible with clear borders. Finally, the designer can select a visual object by clicking it, and it will be highlighted with a blue frame.

Tutorial: The second version of the tutorial has a one-column style, and the figures are in the same pages as text. Furthermore, it provides better explanation of Uvis concepts that were problematic in phase 1.

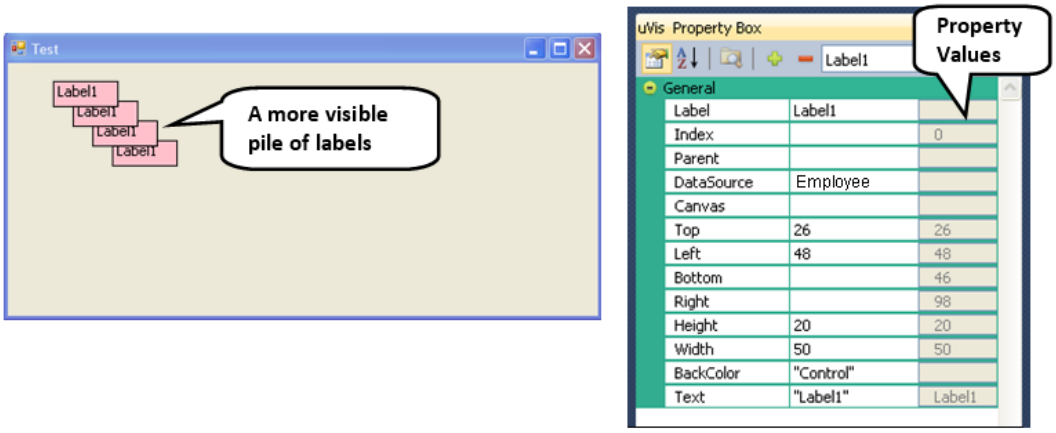


Figure 6.9: Changes in version 2 of the Uvis environment

6.5 Second Phase of Evaluation

This phase was carried out with three participants with different IT skills to get a feeling of how accessible the Uvis system is.

The changes made in the second version of Uvis did not make a visible difference. In fact, one of the changes (the property value column) caused confusion. Let us look at the details.

6.5.1 The Participant's Background

- **Participant 2**
  - **Gender:** female
  - **Age:** 29
  - **Position:** a BSc student in biology.
  - **IT skills:** novice IT user, has basic knowledge of MS word and power-point.
- **Participant 3**
  - **Gender:** male
  - **Age:** 26
  - **Position:** a MSc student in IT.

  - **IT skills:** expert IT user, has knowledge about programming, but has no visualization design experience.

- **Participant 4:**
  - **Gender:** male
  - **Age:** 25
  - **Position:** a PhD student in IT.
  - **IT skills:** expert IT user, has knowledge and experience in programming, but has no visualization design experience.

6.5.2 The Usability Study Settings

- **Tutorial:** Uvis tutorial version 2.
- **Test duration:** For Participant 2, it lasted 1 hour and 15 minutes. For participant 3, it lasted 1 hour and 40 minutes, while for participant 4, it lasted 30 minutes only.
- **Procedure:** The tests for participants 2 and 3 were carried out in a common room in a student dorm, while the test for participant 4 was carried out in a lab. The participants were asked to read the tutorial, follow the steps they are asked to do, and think aloud meanwhile. At the end of each tutorial section, the participant were asked to carry out a task and answer a few question to check their understanding.
- **Tasks:** Participant 2 carried out tasks 1 and 2, version 2 (Figure 6.6). Participant 3 and 4 carried out tasks 1,2,3, and 4, version 2 (Figure 6.6).
- **Understandability Questions:** Participant 2 was asked questions 1 and 2, version 2, while participant 3 and 4 were asked questions 1,2,3 and 4.

6.5.3 Qualitative Results:

Like participant 1, all participants could easily learn some concepts of the Uvis system (e.g. Drag-drop, immediate visual feedback, etc.) Noticeably, participant 4 did not

encounter any usability problem, but gave a few suggestions. However, participants 2 and 3 encountered problems.

A summary of the observed problem is given as follows.

- **Problem 1: Connection between visual objects and table rows:** Like participant 1, participant 2 could not explain that each visual object is connected to a data row. The tutorial made things worse, particularly, page 9 was confusing. "Do I need to produce this?", she asked about the illustration figure (arrows connecting the labels to corresponding rows).

  Participants 3 and 4 did not have that problem, but thought viewing the table would help make the connection easier.

- **Problem 2: Data Model:** Like participant 1, participant 2 could not use the data model in tasks 1 and 2, and participant 2 did not fully understand related tables.

- **Problem 3: Index-based position formulas:** Participant 2 could not figure out how index-based position formulas were calculated(Question 2).

- **Problem 4: Parent property formulas:** Participant 3 could not use the Parent property, or any formula containing references to parent. (Task 4, Question 3).

- **Problem 5: Joining two tables:** Participant 3 could not learn how to use the join operator `(-<)`. He did not specify the right operands (Task 4, Question 3).

6.5.4 Quantitative results:

Figure 6.10 shows the time the participants spent in the tasks, and who succeeded in which task.

6.5.5 Causes and Solutions

- **Cause 1: Inadequate explanation:** Participants 2 and 3 pointed to pieces in the tutorial that did not adequately communicate important concepts such as

	Participant 2 (novice)		Participant 3 (expert)		Participant 4 (expert)	
	Succeeded?	Time (m)	Succeeded?	Time (m)	Succeeded?	Time (m)
Task 1		8	✓	5	✓	2
Task 2		13	✓	14	✓	3
Task 3				7	✓	1
Task 4				13	✓	5

Not Tested

Figure 6.10: Quantitative results of the second phase

visual objects and data. Participant 2 thought she needed to produce the illustration figure in page 9. Furthermore, participant 2 lacked the context. "Where am I? What am I exactly doing now?", she often asked.

This was judged to be a reason behind all the encountered problems.

Solution: Provide context (where the reader is) and objective. Explain index-based position formulas in a procedure-like manner. For instance, start explaining how the first visual object's position properties are calculated, then the second, etc. Furthermore, get rid of ambiguous figures, and show only what the designer is supposed to produce.

- **Cause 2: Being afraid to experiment:** Participants 2 and 3 wanted to experiment more with Uvis formulas, but they were scared of the impact, and the fact that it takes long to go back to the previous state.

  This was judged to be the cause of problems 3 and 4.

  Solution: Provide undo/redo buttons.

- **Cause 3: Invisible Connection between the data model and tables:** Some participants (e.g. participant 2) saw a data model for the first time. The new concept has to be related to something all the participants know (e.g. table).

  This was judged to be the cause of problem 2.

  Solution: Provide table view upon clicking a table box.

Problems	Participants		
	2	3	4
1. Connection between visual objects and table rows	✓		
2. Using and understanding the Data Model	✓	✓	
3. Index-based position formulas	✓		
4. Parent property formulas		✓	
5. Joining two tables		✓	

Not Tested

Causes	Problems					Solutions
	1	2	3	4	5	
1. Inadequate explanation	✓	✓	✓	✓	✓	• Provide better explanation
2. Being afraid to experiment		✓		✓		• Provide undo/redo functions
3. Invisible connection between the data model and tables		✓			✓	• Provide table view upon clicking a table box
4. Invisible connection between parent and child objects				✓	✓	• Allow the parent object to be highlighted with dotted lines when a child is selected • Position child objects on top of parent objects.
5. Poor property value view			✓			• Remove the property value column

Figure 6.11: The second phase problems, causes, and solutions

- **Cause 4: Invisible Connection between parent and child visual objects:** This was judged to be the cause of problem 4.

  Solution: Highlight the parent object with dotted lines when a child is selected. Further, position child objects on top of parent objects.

- **Cause 5: Poor property value view:** None of the participants used the property value column. Participant 3 did not even notice it (He skipped the tutorial part that explained it). Participant 2 looked puzzled when she was reading about it. "I do not understand what this is supposed to do", she commented.

  This was judged to be the cause of problem 3.

  Solution: Remove the property value column.

6.5.6 Changes - The Third Version of Uvis

Development Environment: Version 3 of the Uvis environment was implemented as a result of phase 2 usability tests. Figure 6.12 shows the changes in the environment. A table is shown when the designer double clicks the corresponding table box in the data model. A parent visual object is highlighted with a dotted frame when one of

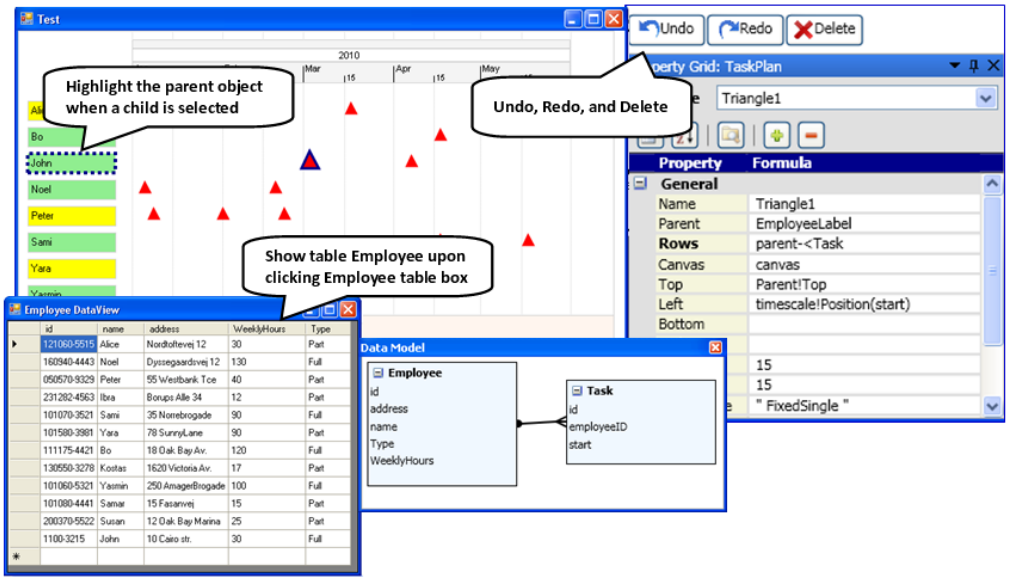


Figure 6.12: The third version of the Uvis environment

its visual children is selected. Further, the child objects are positioned on top of the parent objects upon the specification of `Parent` property (Section 5.3.5). The property value column in Uvis 2 was removed, and the property grid has lighter colours.

Tutorial: Version 3 of the tutorial provided a clear objective for the steps the participant is taking. Furthermore, it provided procedure-like explanation for how the formulas are calculated.

6.6 Third Phase of Evaluation

This phase was carried out with three participants, two of them are potential savvy designers, and one of them is expert (programmer). Moreover, this phase evaluates a lot more Uvis concepts than the previous phases.

The introduced changes in the third version of Uvis fixed some of the encountered problems in previous phase. For example, participants this phase were able to use the data model most of the time. However, other problems remained. For instance, most participants in this phase did not precisely understand the relationship between the visual objects and the table rows.

6.6.1 The Participant's Background

- **Participant 5**
  - **Gender:** male
  - **Age:** 22
  - **Position:** a BSc student in Computer Science
  - **IT skills:** expert user, has knowledge of programming, but no knowledge of excel formulas.
- **Participant 6**
  - **Gender:** male
  - **Age:** 18
  - **Position:** a first year mechanical engineering student.
  - **IT skills:** savvy designer, has basic knowledge of programming.
- **Participant 7**
  - **Gender:** female
  - **Age:** 17
  - **Position:** student.
  - **IT skills:** savvy designer, knows basic math, and has created charts with Excel formulas before.

6.6.2 The Usability Study Settings

- **Tutorial:** Uvis tutorial version 3.
- **Test duration:** For Participant 5, it lasted 1 hour and 40 minutes. For participant 6, it lasted 1 hour and 50 minutes, while for participant 7, it lasted 2 hours and 20 minutes.
- **Procedure:** The tests for participants 6 and 7 were carried in a lab, while the test for participant 5 was carried out at a public library. The participants were asked to read the tutorial, follow the steps he is asked to do, and think aloud meanwhile. At the end of each tutorial section, the participants were asked to carry out a task and answer a few question to check their understanding.
- **Visual Tasks:** All participants carried out tasks 3, version 3 (Figure 6.7).
- **Questions:** All participants were asked to fill in the form in section 6.3.3.

6.6.3 Qualitative Results

- **Problem 1: Connection between visual objects and table rows:** Participants 6 and 7 had difficulties explaining the relationship between visual objects and table rows. To them, the visual objects (labels) come from the table somehow. Participant 5, though, could point to the direct relationship between a visual object and a data row.
- **Problem 2: Inability to check the correctness of the visualization:** Participant 7 came up with the right `Rows` formula for task 2, B, but changed her mind because she did not see a visual difference. She could not confirm her solution.
- **Problem 3: Conditional formulas:** Participant 6 could not figure out how to use conditional formulas .
- **Problem 4: Order by formulas:** Participant 5 could not learn how to use order by formulas.

		Participant 5 (expert)		Participant 6 (savvy)		Participant 7 (savvy)	
		Succeeded?	Time (m)	Succeeded?	Time (m)	Succeeded?	Time (m)
Task 1	A	✓	3	✓	3	✓	10
	B	✓	4	✓	4	✓	10
	C		1	✓	4	✓	5
Task 2	A		2		4	✓	4
	B	✓	3		9		10
Task 3		✓	15	✓	9		14
Task 4		✓	9		5	✓	13

Figure 6.13: The third phase quantitative results

- **Problem 5: Complex visual objects:** All participants spent significant time finding their way through task 3 because it had some mathematical barriers (e.g. inner radius, outer radius, etc.)

6.6.4 Quantitative Results

Figure 6.13 gives an overview of the quantitative results of the third phase.

6.6.5 Causes and Solutions

- **Cause 1: Participants skip tutorial parts** Most participants tend to skip parts in the tutorial that do not catch their attention. Unfortunately, some of these parts might be crucial to the Uvis concepts understanding. For instance, explaining how visual objects and rows are related.

  Solution: Provide a power-point tutorial that proceeds step by step so that the participant tends to focus on one thing at a time. The textual tutorial will still be there as a reference.

- **Cause 2: Insufficient data/feedback** In many cases, visual feedback is not sufficient for the designer to check the correctness of the visualization.

  Solution: Provide the inspector (See chapter 3 for more details)

- **Cause 3: Lack of examples of complex visual objects**

Problems	Participants		
	5	6	7
1. Connection between visual objects and table rows		✓	✓
2. Inability to check the correctness of the visualization			✓
3. Conditional formulas		✓	
4. Order by formulas	✓		
5. Complex visual objects	✓	✓	✓

Causes	Problems					Solutions
	1	2	3	4	5	
1. Participant skip tutorial parts	✓	✓	✓	✓	✓	• Provide a power point tutorial that advances step by step
2. Insufficient data/feedback	✓	✓				• Inspector (show relationship between visual objects and data, and the relationship between visual properties and values).
3. Lack of examples of complex visual objects					✓	• Provide examples of complex visual objects (e.g. pie slice).

Figure 6.14: Causes and solutions for problems observed in phase 3

Solution: Provide documentation that gives examples of complex visual objects (e.g. pie slice).

6.6.6 Changes - The Fourth Version of Uvis

Development Environment: The fourth version of the Uvis environment was implemented as a result of phase 3 usability tests (Figure 6.15). The inspector was added to the version.

Tutorial: The fourth version of the tutorial is power-point based. The highlight of the tutorial is that it shows information bit by bit so that participants do not skip the parts.

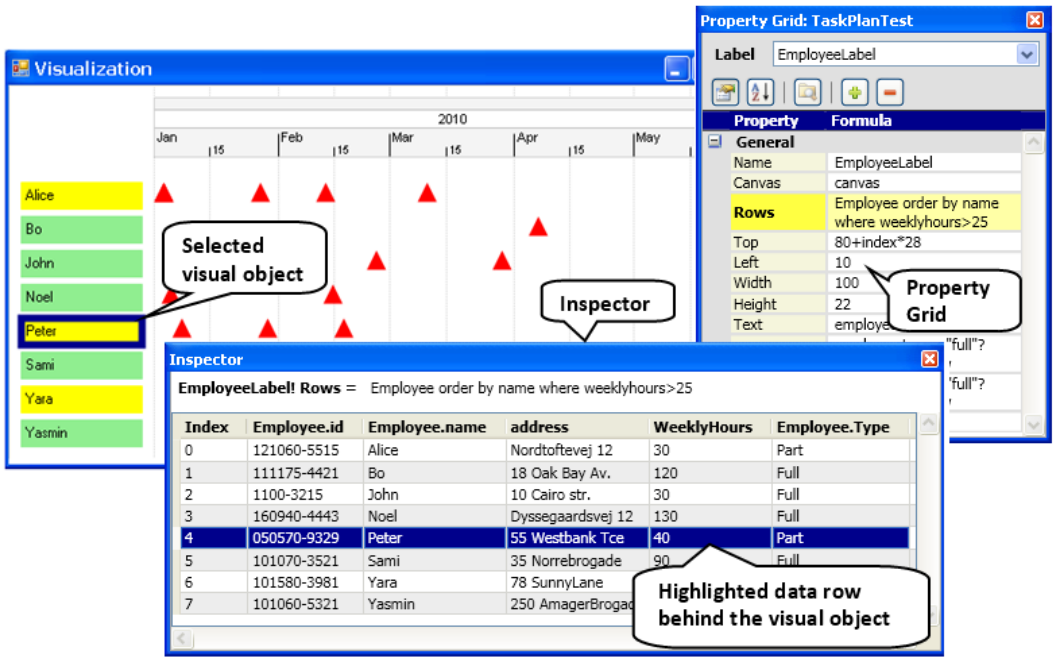


Figure 6.15: The fourth version of the Uvis environment

6.7 Fourth Phase of Evaluation

This phase was carried out with three participants who qualify as savvy designers. The changes introduced in the fourth version of Uvis removed most of the usability problems encountered in the previous phase. For instance, the participants understood the relationship between the visual objects and the data tables. Furthermore, most participants were able to check the correctness of the visual tasks.

6.7.1 The Participant's Background

- **Participant 8**
  - **Gender:** female
  - **Age:** 55
  - **Position:** a professional musician
  - **IT skills:** savvy IT user, has knowledge of database tables, also knows a bit about excel formulas.

- **Participant 9**
  - **Gender:** male
  - **Age:** 60
  - **Position:** businessman.
  - **IT skills:** savvy IT user, has basic knowledge of excel formulas.
- **Participant 10**
  - **Gender:** male
  - **Age:** 53
  - **Position:** a philosophy graduate.
  - **IT skills:** savvy IT user, knows basic math, and has written simple programs before.

6.7.2 Usability Study Settings

- **Manual:** Uvis tutorial version 4.
- **Test duration:** For Participant 8, it lasted 2 hours. For participant 9, it lasted 1 hour and 50 minutes, while for participant 10, it lasted 1 hour and 30 minutes.
- **Procedure:** The tests for participants 8 and 9 were carried at their house, while the test for participant 10 was carried out at a public library. Each participant was asked to read the tutorial, follow the steps he/she is asked to do, and think aloud meanwhile. At the end of each tutorial section, the participant was asked to carry out a task. At the end of the test, the participant filled in a form.
- **Visual tasks:** All participants carried out the third version of the tasks (Figure 6.7).
- **Questions:** All participants were asked to fill in the form in section 6.3.3.

		Participant 8 (savvy)		Participant 9 (savvy)		Participant 10 (savvy)	
		Succeeded?	Time (m)	Succeeded?	Time (m)	Succeeded?	Time (m)
Task 1	A	✓	4	✓	3		2
	B		4	✓	2	✓	4
	C		4	✓	2	✓	5
Task 2	A	✓	3	✓	5	✓	1
	B	✓	5	✓	3	✓	3
Task 3			17	✓	23		18
Task 4		✓	6	✓	11	✓	2

Figure 6.16: Quantitative results of the fourth phase tests

6.7.3 Qualitative Results

The participants encountered these problems.

- **Problem 1: Visual object disappearing on error:** Participants 8 and 9 encountered a problem with Task 3. When they set incomplete specifications for a `PieSlice` object. The object disappeared. The participants dragged and dropped a new `PieSlice` object.
- **Problem 2: Inability to compare two visual object specifications:** Participant 9 wanted to see the specifications of an existing `PieSlice` object with a new one he dragged side by side. He did it on a paper and pencil.
- **Problem 3: Data field formulas:** Participant 8 explained that she did not understand data field formulas after carrying out task 1.

6.7.4 Quantitative Results

Figure 6.16 shows the quantitative results of the fourth phase tests.

6.7.5 Causes and Solutions

Figure 6.17 shows an overview of the problems, causes, and solutions of the fourth phase.

Problems	Participants		
	8	9	10
1. Visual object disappearing on error	✓	✓	
2. Inability to compare two visual object specifications		✓	
3. Data field formulas	✓		

Causes	Problems			Solutions
	1	2	3	
1. Inadequate visual feedback for pie slices	✓			• Show pie slices even when there is an error
2. Inadequate Explanation of data field formulas			✓	• Explain the data field formulas better.
3. Lack of support for comparing two visual objects		✓		• Provide copy/paste functions.

Figure 6.17: The fourth phase problems, causes, and solutions

- **Cause 1: Inadequate visual feedback for pie slices:** Designers did not get an easy feedback when there was an error with the pie slice object. It just disappeared.

  Solution: Show the pie slice (in design mode only:) even if they have erroneous specifications, but it should be obvious that there is a problem with the specifications.

- **Cause 1: Inadequate Explanation of data field formulas** Participant 8 did not get the fact that data field formulas refer to field names that exist in the data model.

  Solution: In the tutorial, link the explanation to the data model fields.

- **Cause 3: Lack of support for comparing two visual objects:**

  Solution: An ideal solution would be to allow viewing more than one property grid for different visual objects. For time reasons, this solution was not implemented. Instead, copy/paste functions were provided hoping that designers can copy the object they want to refine.

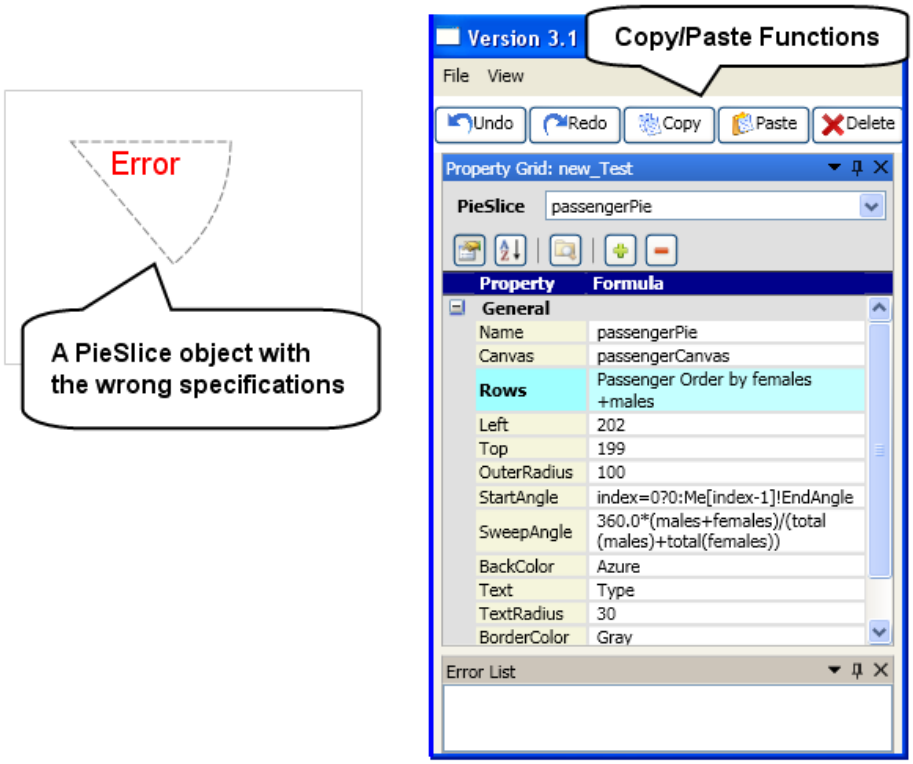


Figure 6.18: The changes in the fifth version of Uvis

6.7.6 Changes - The Fifth Version of Uvis

Figure 6.18 shows the changes in the fifth version of Uvis. Copy and paste functions were added. A `PieSlice` becomes dotted with an "error" text when it gets the wrong specifications. This only happens in design mode. This way, the designer gets feedback about what is happening.

The fifth version of the tutorial explains data field formulas in connection to the data model.

Section 5.3 explains the version in more detail.

6.8 Summary

Figure 6.19 provides a summary of the problems the participants encountered in the usability studies. As Uvis evolved, fewer problems were encountered. In conclusion, many usability problems were reduced. For instance, it became easier to debug visu-

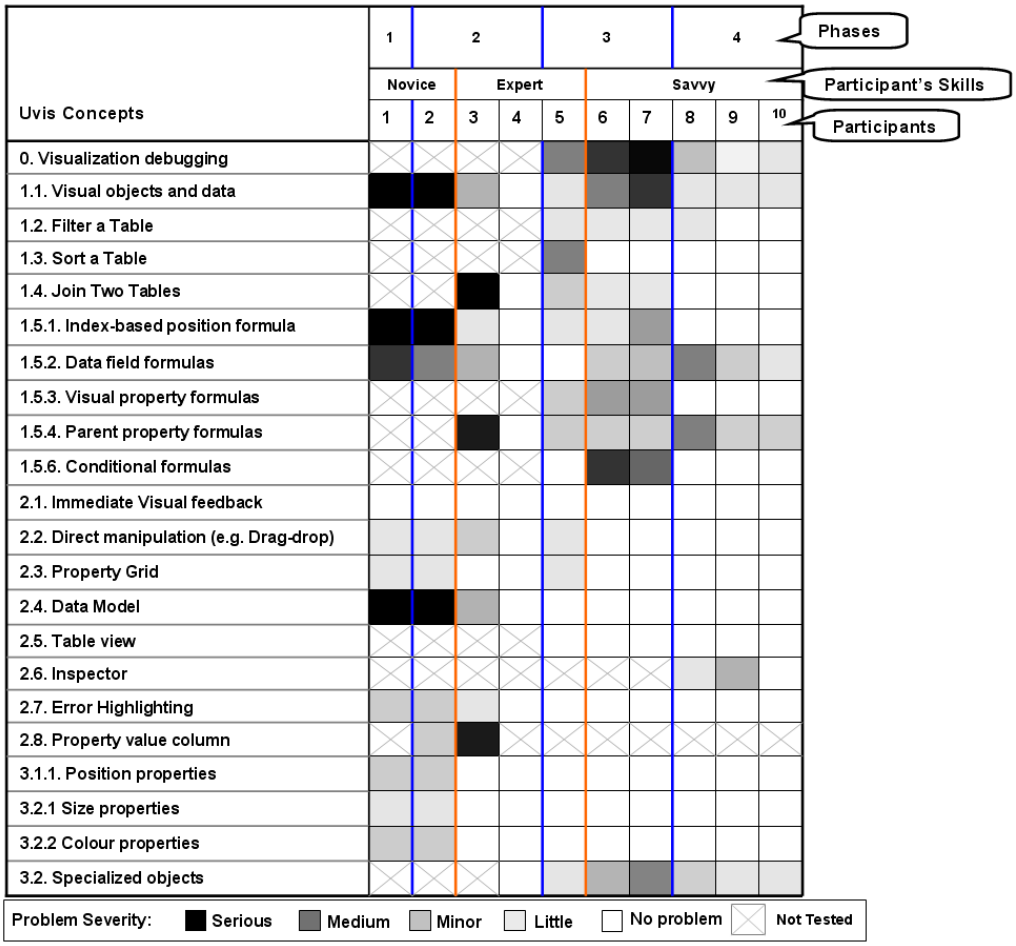


Figure 6.19: The fourth phase problems, causes, and solutions

alizations, and understand the relationship between visual objects and data. However, some concepts (e.g. `Parent`) are still not straightforward.

7

Evaluation

7.1 Introduction

This chapter presents different types of evaluation of Uvis. First, I compare Uvis with other tools. The ideal would be to make usability tests for the other tools, but this will introduce bias, and require a lot of time and resources. Therefore, I compare Uvis with other tools using comparative analysis (Section 7.2) and the cognitive dimensions of notations (Section 7.3.)

Finally, I evaluate Uvis using an experimental evaluation that measures the designer's performance (Section 7.4.)

7.2 Tool Comparative Analysis

This section compares three tools with Uvis using a custom scatter plot example (Figure 7.1). The example shows high readings of temperature in a given city. The readings are taken from 1 June 2011 to 1 October 2011. The dots represent the readings, and so far it looks like a conventional chart. However, we want to customize the colour of the dots. If the dot is showing the highest temperature, it is black. Otherwise, if the dot is showing a temperature greater than 25, it is red. The rest of the dots are orange.

Although the example is simple, it was selected because it can be made with all the selected tools even though they are geared for different areas in the visualization world.

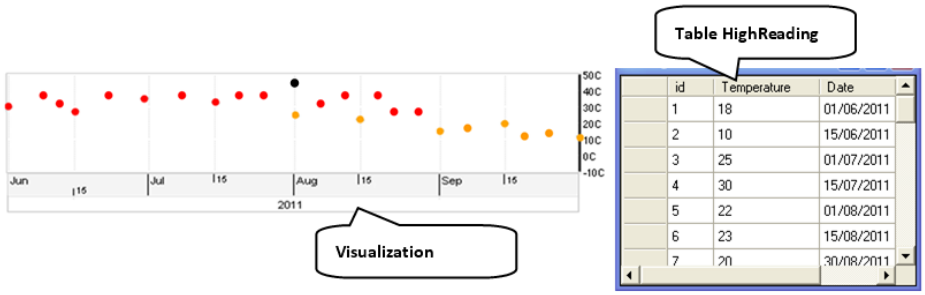


Figure 7.1: A custom scatter plot based on table HighReading

7.2.1 Selected Tools

Three visualization tools were selected for evaluation: Prefuse (5), Improvise (22), and Protovis (6). The tools were selected based on: Support for custom visualizations, how recent they are, whether they are general-purpose, difference of approaches, and finally the number of citations.

All the selected tools support the creation of custom visualizations, have been developed in the last decade, and are general-purpose. Also the tools have different approaches to visualization creation.We only selected a representative tool from tools similar in approach or cognitive aids. For instance, we excluded Flare (23) since it adapted its design from Prefuse. Likewise, we excluded D3 (24) as it borrows a lot of its concepts (e.g. helper functions) from Protovis.

The selected tools were ranked based on the total number of citations on ACM Portal and IEEE website.

7.2.2 Prefuse

Figure 7.2 shows the specifications of a custom scatter plot with Prefuse. First, a visualization object is created and bound to data (lines 1-3). Prefuse uses an `AxisLayout` abstraction that supports plots (lines 4 and 5). The to-be-visualized fields are passed in the `AxisLayout` constructor.

Actions are objects that perform visual mappings (lines 8-10). There are many kinds of them. For instance, `ColorAction` can make a colour property (e.g. border colour or background colour) show data. The `orangeColor` variable makes all visual objects orange (line 8). It sets the `FILLCOLOR` (background colour) of all visual objects

```
a
1.  Visualization vis = new Visualization();
2.  Display display = new Display(vis);
3.  vis.add("HighReading", data);

b
4.  AxisLayout x_axis = new AxisLayout(" HighReading ", "Date", Constants.X_AXIS, VisiblePredicate.TRUE);
5.  AxisLayout y_axis = new AxisLayout(" HighReading ", "Temperature", Constants.Y_AXIS, VisiblePredicate.TRUE);

c
6.  Predicate p1 = (Predicate)ExpressionParser.parse("Tempreature > 25");
7.  Predicate p2 = (Predicate)ExpressionParser.parse("Tempreature=MAX(Tempreature)");

8.  ColorAction Orangecolor = new ColorAction("data", VisualItem.FILLCOLOR, ColorLib.getColor(255, 128,0));
9.  ColorAction redColor =new ColorAction("data", VisualItem.FILLCOLOR,p1, ColorLib.getColor(255, 0,0));
10. ColorAction blackColor =new ColorAction("data", VisualItem.FILLCOLOR, p2, ColorLib.getColor(255, 0,0));

d
11. ActionList draw = new ActionList();
12. draw.add(x_axis);
13. draw.add(y_axis);
14. draw.add(redColor); draw.add(orangeColor); draw.add(blackColor);
15. vis.putAction("draw", draw);
16.

e
17. vis.setRendererFactory(new RendererFactory()
18. { AbstractShapeRenderer sr = new ShapeRenderer(7);
19. Renderer arY = new AxisRenderer(Constants.FAR_Right, Constants.CENTER);
20. Renderer arX = new AxisRenderer(Constants.CENTER, Constants.FAR_BOTTOM);});

21. AxisLabelLayout x_labels = new AxisLabelLayout("xlab", x_axis);
22. AxisLabelLayout y_labels = new AxisLabelLayout("ylab", y_axis);
23. draw.add(x_labels);
24. draw.add(y_labels);
25. y_axis.setRangeModel(new NumberRangeModel(-10, 50, -10, 50));

f
26. final Ellipse2D TempreatureEllipse = new Ellipse2D.Double();
27. x_axis.setLayoutBounds(TemperatureEllipse);
28. y_axis.setLayoutBounds(TemperatureEllipse);
```

Figure 7.2: Creating a custom scatter plot with Prefuse. a: binding the visualization to data, b: defining time and numeric axes, c: defining a conditional visual mapping, d: associating the visual mappings with the visualization, e: defining tick marks and associating them with the axes. f: defining ellipses representing the temperature readings

to orange. However, the `redColor` variable makes objects that conform to a condition red (line 9). The condition is specified by a predicate that checks if the temperature fields are greater than 25. This predicate is specified at line 6. The actions are attached with the visualization object (lines 11-15).

The axes are positioned using a `RenderFactory` class (lines 17-20), and tick marks of the axes are generated using an `AxisLabelLayout` class (lines 21-24). The tick marks are associated with their corresponding axes (line 25).

Finally, ellipses are chosen as visual objects to represent the temperature readings, and associated with the axes defined previously (lines 26-28).

Conclusion: There are many abstractions that designers have to know and create (e.g. `AxisLayout`, `RenderFactory`). The separation of actions from the visualizations, predicates, and their properties can facilitate the management of code and allow reuse, but reduces the understandability of the visual mappings. A designer might be wondering "which visual object or property does this action relate to?".

7.2.3 Protovis

Figure 7.3 shows the specifications of a custom scatter plot with Protovis. First, a visualization object is defined (lines 1-4). Protovis uses non-visual scale classes for creating time and numeric axes (lines 5-11). The designer uses them to generate tick data. `Rule` and `Label` visual objects are used to draw the axes based on the tick data (lines 12-18).

`Dot` objects are bound to data (an array that corresponds to the `HighReading` table) (lines 19-21). The `Left` and `Bottom` properties position the `Dot` objects horizontally and vertically (lines 22 and 23). The designer specified expressions for the two properties that call functions provided by the scales that calculate the positions based on temperature and date fields. Finally, a conditional expression for the `FillStyle` (background colour property) sets the colour of dots that show the highest temperature black. Otherwise, it sets the colour red for dots showing temperature greater than 25 red. Otherwise, they are orange (lines 24 and 25).

Development Environment (Protoviewer): The visualization can be built with the Protoviewer development environment (Figure 7.4). This has several advantages. Designers can see the resulting visualization immediately as they are modifying

```
a
1.  var w = 400, h = 400;
2.  var vis = new pv.Panel()
3.  .width(w)
4.  .height(h);

b
5.  var y = pv.Scale.linear(-10, 50).range(0, h),
6.  vis.add(pv.Rule)
7.  .data(y.ticks())
8.  .bottom(y)
9.  .strokeStyle(function(d) d ? "#eee" : "#000")
10. .anchor("left").add(pv.Label)
11. .text(y.tickFormat);

12. var x = pv.Scale.linear(new Date(2011,6,1), new Date(2011,10,1));
13. vis.add(pv.Rule)
14. .data(x.ticks())
15. .left(x)
16. .strokeStyle(function(d) d ? "#eee" : "#000")
17. .anchor("bottom").add(pv.Label)
18. .text(x.tickFormat);

c
19. vis.add(pv.Panel)
20. .data(HighReading)
21. .add(pv.Dot)
22. .left(function(d) x(d.Date))
23. .bottom(function(d) y(d.Tempreature))
24. .fillStyle(function(d) pv.max(data.Tempreature) = d.Tempreature ?
25.  "#000000" : d.Tempreature > 25? "#FF0000" : "#FF6600");
```

Figure 7.3: Creating a custom scatter plot with Protovis a: defining the visualization, b: defining the numeric (temperature) and time scales (axes). c: defining dots and visually mapping them to temperature and date fields according to the scales

the source code. Moreover, clicking a visual object, designers can view the position values (x and y) of the object. This can help inspecting the object.

Conclusion: Protovis provides non-visual scale classes that facilitate the construction of axes. The axes are not defined directly. Instead, primitive objects such as `Label` and `Rule` are used for drawing the axes. This separation increases flexibility (e.g designers might obtain a custom axis in this way), but increases the steps of such a common task. Unlike Prefuse actions, the declarative expressions for the `Dot` visual objects are not separated from the visual properties. This increases visibility and understandability.

7.2.4 Improvise

The designer starts by importing the `HighReading` table. The Lexicon panel displays imported data sets, grouped by relational schema. To define a scatter chart, the designer chooses `Plane View 2D` object from the list of visual objects. To define visual mappings for the visual object, the designer chooses `Layer.Projection` from the list

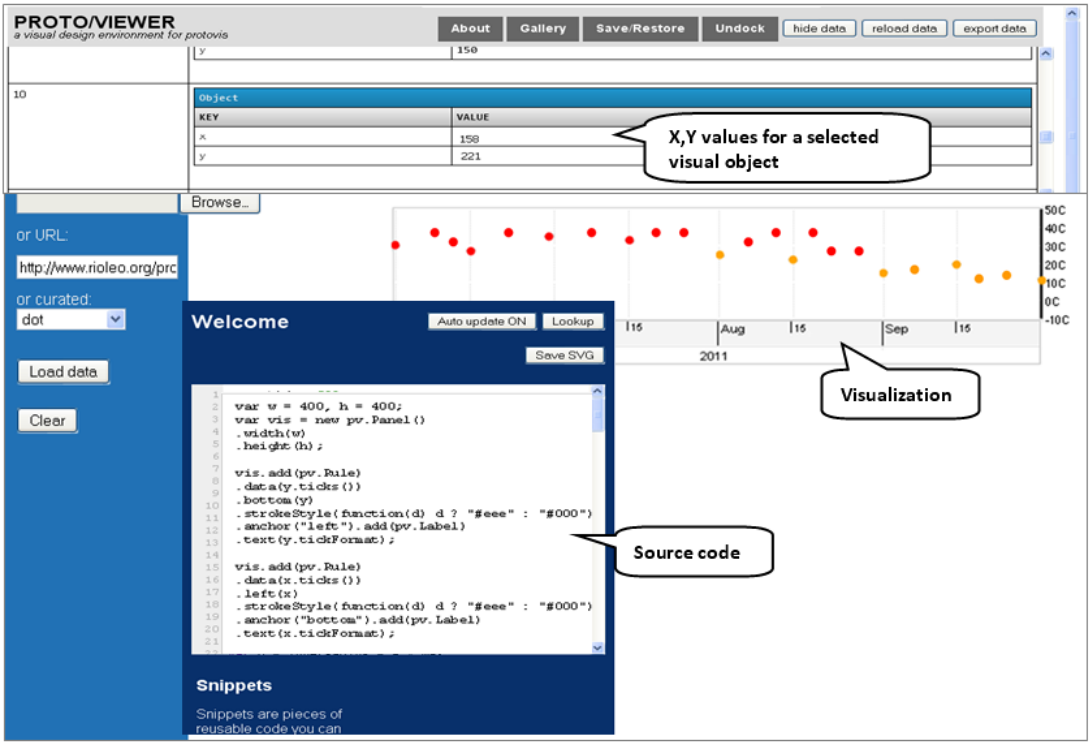


Figure 7.4: Creating a custom scatter plot with the Protovis environment (Protoviewer)

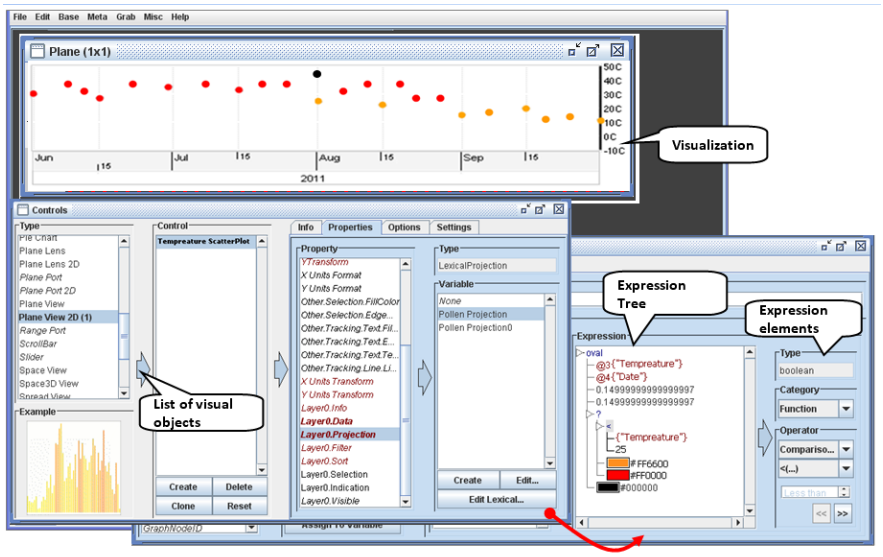


Figure 7.5: Creating a custom scatter plot with Improvise

of properties. He clicks "Create" to create a new projection (visual mapping). This leads him to a new panel (`Lexicon`) where he can define expressions.

We want to define this expression for the background colour property.

```
Temperature > 25 ?  "red":  "orange"
```

This expression has to be built step-by-step using combo boxes that provide the available Expression elements (Figure 7.5). First, the designer creates the conditional part of the expression by choosing `Function` from the `Category` combo box, and `Other` and `?(boolean,Color,Color)`. Improvise shows the result as a conditional expression tree with default colours as results for the true and false expressions.

Second, the designer can manipulate the conditional statement parts by clicking the tree nodes. To create a comparison condition, the designer chooses `Function` from the `Category` combo box, and `Comparison` and `>(...)` from the `Operator` combo boxes. Third, to make one of the nodes refer to the `Temperature` field, the designer clicks the node and chooses `Attribute` from the `Category` combo-box. Improvise displays the available fields, and the designer just selects (clicks) it.

Comments: In general, data transformations and visual mappings rely heavily on dialogues. For instance, even a simple expression takes long to create. The environment forces the designer to use combo-boxes that have the expression elements. It is not easy to find the expression elements. Moreover, the longer the expression, the harder it is to read.

7.2.5 Uvis

Figure 7.6 shows the textual specification of the custom scatter plot with Uvis and Figure 7.7 shows the environment where the chart was developed.

To create the time and numeric axes, the designer dragged `HTimeScale` and `VNumericScale` visual objects from the toolbox and dropped them on a form. The designer moved and resized them until they looked right. The environment sets position properties (i.e. `Top`, `Height`, etc.) accordingly. To define the range of time and numbers the scales show, the designer typed the value of the `Range` property in the property grid (lines 5 and 11 in Figure 7.6).

To create dots representing the temperature reading, the designer drags and drops an `Ellipse`. The designer typed formulas for the position properties (`Top` and `Left`). The formulas call position functions provided by the scales to calculate the positions

```
a
1.  Form: form
2.  Width:600
3.  Height:250

b
4.  HTimeScale: tScale
5.  Range: #1-6-2011#, #1-10-2011#
6.  Canvas: canvas
7.  Width: 530
8.  Top: 150
9.  Left: 10

10. VNumericScale: nScale
11. Range: -10, 50
12. Orientation: Orientation.Right
13. Height: 90
14. Top: 40
15. Left: 10

c
16. Ellipse: Temperature Ellipse
17. Rows: HighTemperature
18. Top: nScale!Position(Temperature) - Height/2
19. Left: tScale(Date)!Position(Date) - Width/2
20. BackColor: MAX(Temperature)=Temperature ? Black :
21. Temperature >25? Red : Orange
```

Figure 7.6: The specifications of the custom scatter plot with Uvis

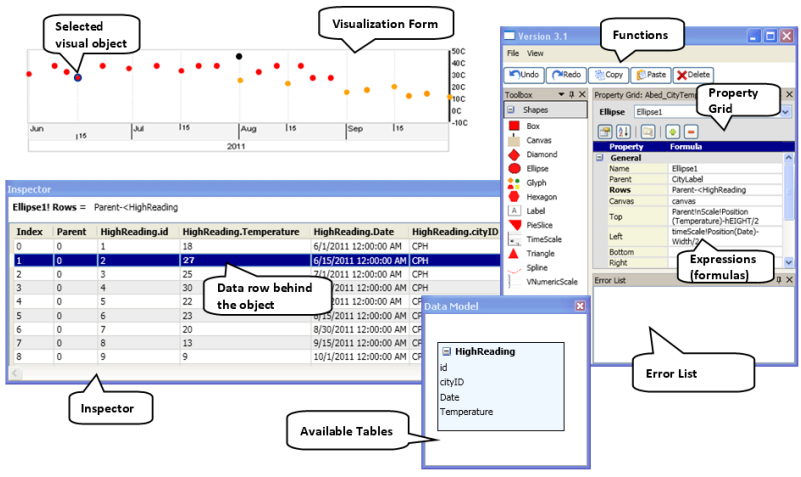


Figure 7.7: The scatter plot visualization in the Uvis environment

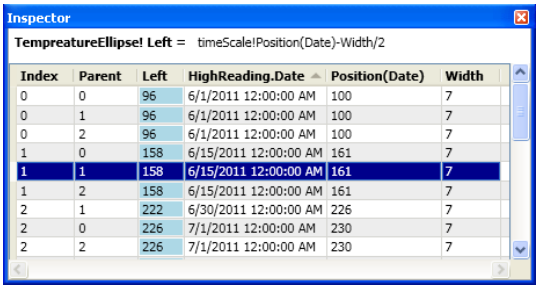


Figure 7.8: The Left expression values

based on temperature and date fields (lines 18 and 19 in Figure 7.6). Finally, a conditional expression for the `BackColor` (background colour property) sets the colour of ellipses (line 21 in Figure 7.6).

Development Environment: The environment has several advantages. Designers can drag, drop, resize visual objects (Direct manipulation), and they can see the resulting visualization immediately as they are updating the expressions.

The inspector shows data for a bundle of visual objects. It shows the data rows behind the visual objects (Figure 7.7). Further, it shows the values of an expression and its sub-expressions (Figure 7.8).

Comments: Unlike Prefuse, Protovis, and Improvise, Uvis deals only with visible visual objects. Like Protovis, Uvis uses declarative expressions that directly define the visual properties, but there is no need to define variables, and the sequence of specifying the expressions is free. Like Improvise, the environment shows the available visual objects, but it allows the designers to drag, drop, and resize them (as long as the position and size properties do not have dynamic expressions) rather than textually setting them.

7.3 Evaluating the Tools with the Cognitive Dimensions of Notations

This section uses the framework of cognitive dimensions of notations (CDs) (12) to evaluate how well the selected tools in the previous section support custom visualizations. The framework can be used as guidelines for designing and evaluating a notional system and the environments it is manipulated in. It provides cognitive dimensions that need to be addressed for several kinds of tasks. The user tasks can be classified into

four types: Transcription (copying content from one structure to another), incrementation (adding information without altering the structure), modification (changing the existing structure possibly without adding new content), and exploration (combining incrementation and modification taking into consideration that the desired end might not be known in advance) (52). According to this definition, implementing a custom visualization is an exploration task in essence.

The cognitive dimensions that are important to look at when designing or evaluating tool support for exploration tasks are: Abstractions, hidden dependencies, premature commitment, progressive evaluation, viscosity, visibility, and juxtaposability (52). Ideally, systems that support exploration tasks (e.g. implementing a custom visualization) should have low viscosity, few hidden dependencies, few premature commitments, few abstractions, and high visibility and juxtaposability.

Let us look at how the selected tools perform in these dimensions.

7.3.1 Abstractions

The Abstractions dimension assesses the abstractions that encapsulate implementation details and the mechanism to manage them. Although abstractions can make the specifications shorter and sometimes fit the domain better, systems that require learning many abstractions have an *abstraction barrier*. Furthermore, exploration tasks do not tolerate many abstractions.

Prefuse is an example of a system that has an abstraction barrier. For instance, there are many subtypes of `Layout`, `RenderFactory`, and `Action` to learn. The abstractions can be extended programmatically by Java programming, but this requires in-depth knowledge of Java.

Protovis has fewer abstractions to learn than Prefuse, but some programming abstractions (e.g. variables, anonymous functions) are necessary to learn. Protovis abstractions can be extended programmatically with JavaScript.

Like Prefuse, Improvise has many abstractions. For instance, there are many panels and expression parts (e.g. conditional statements, functions, etc.) and the designers need to be aware of their meaning, and how to manipulate them, etc. Like Prefuse, Improvise abstractions can be extended with Java.

Uvis formulas resemble spreadsheet expressions, but obviously have more abstractions than spreadsheets. For instance, a Uvis formula can refer to data fields, visual

properties, etc. However, Uvis has relatively few abstractions. For instance, there are no variables and rendering objects. Uvis does not allow defining new abstractions.

7.3.2 Hidden Dependencies

The hidden dependencies dimension assesses whether dependencies between entities are hidden or visible. Hidden dependencies slow down information finding and can potentially increase the risk of error. Exploration tasks tolerate only a few hidden dependencies.

Most Prefuse abstractions have hidden dependencies. For example, the layout action implicitly overrides a specific visual mapping of size and position properties.

Protovis expressions can depend on variables. Such dependencies can be hard to see in textual specifications. More advanced visualizations use layout classes that position visual items implicitly (e.g. tree maps), or some operators such as "Parent" and "Sibling" that have hidden dependencies.

In Improvise, it is hard to derive the elements of an expression, particularly, if the expression contains variables or other sub-expressions. These can be viewed in other panels.

Uvis formulas can depend on other visual properties. The properties can have their own formulas, and so on. When designers change an expression, it is hard to know the implications of such a change. Furthermore, more advanced visualizations such as hierarchical visualizations use operators (e.g. `Parent`) that result in hidden dependencies.

All the surveyed tools except for Uvis do not explicitly show which particular visual property depends on which field. The Uvis environment shows that using the inspector (Figure 7.8).

7.3.3 Premature Commitment

The premature commitment dimension assesses whether there are any constraints on the order in which tasks must be accomplished. Premature commitment is harmful for exploration tasks.

Since the specifications are program-like, Prefuse and Protovis impose constraints on the sequence in which visualizations are defined. For instance, if a property depends on another, the independent one has to be defined first.

Improvise imposes a strict sequence on how some things are done. Constructing the expression step-by-step is an example of strict sequencing, and having to navigate from panel to panel to carry out visual mappings is another one.

Uvis specifications are sequence-free. At run time, the kernel finds out the sequence of execution. If the designer types a formula that refers to a property that does not exist yet, Uvis kernel flags an error, but the application still runs.

7.3.4 Progressive Evaluation

The progressive evaluation dimension assesses how easy it is to evaluate and obtain feedback on an incomplete task. Progressive evaluation is important for exploration tasks.

In Prefuse, it is not easy for a designer to obtain visual feedback of the specifications. The source code has to be run in another setting to obtain feedback.

Improvise bridges that gap with an immediate visual feedback feature. However, the visual feedback can be over-shadowed with many editing panels.

Protoviewer and the Uvis environment provide a separate design panel that is updated immediately when the specifications are changed. The Uvis environment provides similar kinds of feedback as traditional environments such as highlighting erroneous formula parts, error, and warning lists. In addition, the environment shows the formula values in a separate panel that is updated when the formula changes (Figure 7.8.)

7.3.5 Viscosity

The viscosity dimension assesses the cost of making small changes. It is costly to make a small change in viscous systems. Viscosity is harmful for exploration tasks. We consider two types of viscosity. First, *repetitive viscosity* means a single goal-related change which requires many repetitive actions. Second, *knock-on viscosity* means a change in one part affects other related parts.

Prefuse is based on an object oriented language (Java.) Hence, inheritance can reduce repetitive viscosity. For instance, a change can be made in a parent class rather than all inheriting classes. Modern development environments can help with small knock-on changes such as changing a variable name that is used in many places (refactoring.) Nevertheless, changing Prefuse specifications requires in-depth knowledge of the language constructs and programming concepts.

Like Prefuse, the Protovis language has low-repetitive viscosity since it supports inheritance for visual objects. Moreover, Protovis allows other changes easily, for instance, changing the visual object type. The environment (Protoviewer) does not have support for making changes.

Designers who are experienced with Improvise might find some things easy to change. For instance, variables that are referred to from many expressions can be changed in one setting. Otherwise, Improvise is highly viscous. For instance, changing some specialized visual object types (e.g. Plane View) is not possible. In general, a change in Improvise requires navigating across panels.

Like spreadsheets, simple visualizations in Uvis have low viscosity. However, viscosity grows with size. Uvis does not support inheritance, but designers can add properties that have formulas that other visual objects can refer to. In such a case, a change is only required in the designer property. Since Uvis formulas can refer to other formulas elsewhere, a change in one formula might affect other dependant formulas. The Uvis environment shows errors that result from such a change.

7.3.6 Visibility and Juxtaposability

The visibility dimension assesses the ability to view data components easily. Juxtaposability assesses the ability to view two similar components side by side. The two dimensions are generally discussed together due to similarity. Both dimensions are important for exploration tasks.

What data components would a designer want to view when implementing a custom visualization? Many can be considered important. Examples include the currently-designed visualization, the available visual objects and their properties, the visual mappings, the available data, the visualized data, and errors. What needs to be viewed varies from task to task and designer to designer, but a possible solution is to give designers the ability to show or hide components.

Even if Prefuse is integrated with a development environment, only a few components can be visible in one setting. Traditional environments show the source code, the available visual objects, and a list of errors in one setting. However, the designer has to view the currently-designed visualization in another setting.

Protoviewer shows the currently-designed visualization as well as the specifications behind it. Furthermore, designers can view the position property values of a single

selected visual object at a time. Protoviewer does not provide support for comparing the specifications of two similar visual objects.

Improvise shows the currently-designed visualization, but it can be over-shadowed by the editing panels. A panel can only show one expression at a time, and it occupies a lot of space. This does not allow comparing many expressions. Further, many data crucial for the task (e.g. data fields) are buried in combo boxes.

Uvis shows the currently-designed visualization, the properties (and the expressions defining them) of a selected visual object, and a list of errors. Upon selecting a visual object, Uvis shows the data behind that particular object. Further, to allow comparison, the data from other visual objects from the same data source are shown as well. It is also possible to see the defining expressions of all properties of a selected visual object. However, it is not possible to see expressions of two visual objects at the same time.

7.3.7 Summary

The findings of the comparative analysis and the evaluation with the cognitive dimensions of notations can be summarized as follows:

- **All the surveyed tools** suffer from low juxtaposability and high hidden dependencies with slightly different degrees.
- **All the surveyed tools except for Uvis** suffer from high premature commitment and low visibility with slightly different degrees.
- **Prefuse** uses a programmatic approach that relies on specialized modules. The main strength of this approach is the breadth of visualizations it can express due to the many modules it provides. However, there are many abstractions to learn even to construct a simple example like a custom scatter plot. Furthermore, even with a development environment, the approach suffers from low progressive feedback.
- **Improvise** uses an approach that is heavily dependant on dialogues (panels). The main strength of this approach is that the tool provides useful visual objects tailored for some tasks. However, the functionalities are not easy to find. For instance, the conditional expression is buried in a combo box item called "Other".

- **Protovis** uses an approach that relies on primitive visual objects and declarative expressions. The main strength of the approach is that the properties of the visual objects are directly specified. No middle-ware objects (e.g. Prefuse actions) are needed to link visual properties with expressions. However, some programming abstractions (e.g. variables) are still needed to learn the language.

- **Uvis** uses an approach that relies on declarative spreadsheet-like formulas for visual mappings, and a dedicated environment with many features (e.g. drag-drop, visual feedback, etc.). The approach has high visibility, low premature commitment, and relatively few abstractions to learn. However, the approach still suffers from high viscosity (especially when it is a large-sized application).

To sum up, the findings favour notations that use declarative expressions since fewer abstractions are needed to learn in comparison with programming. Furthermore, the findings favour environments that allow exploration (low premature commitment) and have high visibility rather than environments that are dialogue-dependant.

7.4 Experimental Evaluation

This sections reports on a preliminary evaluation study with six potential savvy designers. Unlike the usability studies in chapter 6, this evaluation is not mainly concerned with finding usability problems. Instead, it assesses to what extent designers can succeed on their own. The experimenter does not provide any help. Further, it provides an overall evaluation of the tool, and assesses the impact of the inspector on ease of learning.

7.4.1 Objective

- Evaluating the ease of learning.

- Evaluating the impact of the inspector on ease of learning.

- Identifying the Uvis concepts that are easy or difficult to learn.

7.4.2 The Participant's Background

All the participants were non-programmers. They had no prior knowledge of the Uvis formulas, and had never used the Uvis environment. They have basic knowledge of Excel formulas, algebra, trigonometry, and sequences, and know what a database table is. Further, they know how to read simple visualizations (e.g. bar chart, pie chart, etc.).

In addition to these common skills, some participants have more IT skills.

- **Participant 1:** A 28 year-old male who currently does voluntary work. He is familiar with logical expressions (e.g. AND/OR). He came across the E-R model.
- **Participant 2:** A 22 year-old female biology student.
- **Participant 3:** A 22 year-old male student who is familiar with advanced Excel formulas (e.g. IF, AND, etc.). He has created simple visualizations with the standard tools.
- **Participant 4:** A 19 year-old male student.
- **Participant 5:** A 26 year-old male chef assistant. He came across the E-R model. He has created standard and non-standard charts.
- **Participant 6:** A 27 year-old male loan manager. He came across the E-R model.

7.4.3 Procedure

Each evaluation study lasted 2 hours on average. The studies were carried out in a lab. The participants were divided into two groups: participants 1, 2, and 3 belong to group A while participants 4, 5, and 6 belong to group B. Each participant viewed two screens. One screen showed a power-point based step-by-step tutorial available, and the other showed the Uvis environment. The tutorials for both groups were identical except that the group A tutorial explained about the inspector. Each participant was asked to view the tutorial, and do what it says. The tutorial is divided into sections, at the end of which, designers were given a task to work on their own, but they could go back to the tutorial and/or example solutions.

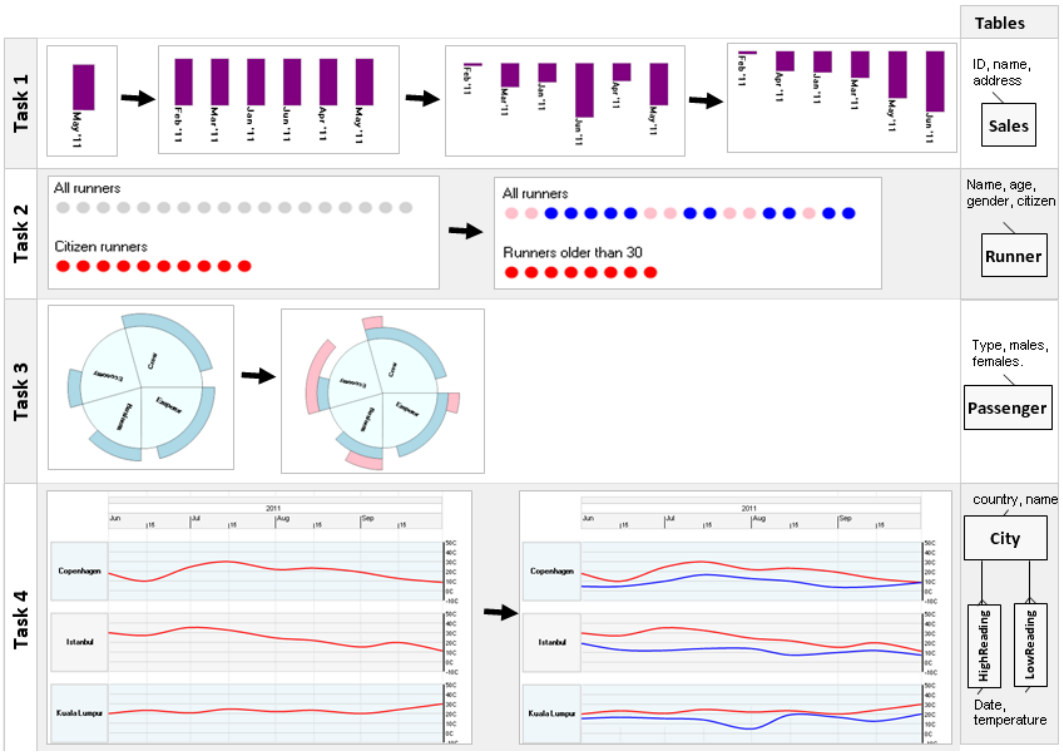


Figure 7.9: The evaluation tasks

Quantitative measures: To evaluate ease of learning, I measured task completion time (T) and the quality of the solution (Q). The quality of the solution was measured by comparing the participant's solution against the optimal solution and then rating it on a scale 0-10.

Qualitative measures: To find out which concepts that are easy or hard to understand, and collect other information related to Uvis, I observed the participants while they used the tool, and asked them to fill the form in section 7.4.5

The detailed documentation can be found at (53).

7.4.4 Tasks

Figure 7.9 shows the tasks the designers carried out in the evaluation. They are the same as the third version of tasks in chapter 6. The tasks are different in layout, and evaluate most Uvis concepts. Moreover, they are relatively simple due to the short experiment duration.

	GA Participants			GB Participants			Summary			
							Time (m)		Quality (0-10)	
	1	2	3	4	5	6	GA	GB	GA	GB
Task 1	T: 12:25 Q: 10	T: 5:30 Q: 10	T: 7:40 Q: 10	T: 13: 37 Q: 9	T: 4:00 Q: 10	T: 25 Q: 7	μ: **8**:31 σ: 3.53	μ: **14**:12 σ: 10.5	μ: **10** σ: 0	μ: **8**.66 σ: 1.57
Task 2	T: 8:20 Q: 8.5	T: 4 Q: 10	T: 4:46 Q: 9	T: 11:30 Q: 5	T: 7:20 Q: 10	T: 14:02 Q: 5	μ: **5**:42 σ: 2.31	μ: **10**:57 σ: 3.38	μ: **9**.16 σ: 0.76	μ: **6**.66 σ: 2.88
Task 3	T: 6:37 Q: 10	T: 15:20 Q: 9	T: 9:20 Q: 10	T: 10:45 Q: 5	T: 15:30 Q: 10	T: 14:05 Q: 5	μ: **10**:25 σ: 4.46	μ: **13**:26 σ: 2.43	μ: **9**.66 σ: 0.57	μ: **6**.66 σ: 2.88
Task 4	T: 4:36 Q: 9.4	T: 7:39 Q: 9	T: 6:26 Q: 10	T: 9:45 Q: 10	T: 9:00 Q: 10	T: 13:10 Q: 9	μ: **6**:13 σ: 1.53	μ: **10**:38 σ: 2.22	μ: **9**.46 σ: 0.5	μ: **9**.67 σ: 0.57

Figure 7.10: Evaluation Quantitative results. T=Time, Q=Solution quality, GA=Group A, and GB=Group B

- **Task 1:** The bars (on top of each other) show a company's monthly sales. Position the bars representing monthly sales like a horizontal list, make the bar heights represent the monthly sales, and order them based on the sales.
- **Task 2:** The ellipses on top show all runners in a marathon. The ones on the bottom show runners that are citizens. For the ellipses on the top, make the male runners blue, and the female ones pink. For the ellipses on the bottom, show only runners older than 30.
- **Task 3:** A pie chart shows several classes of passengers (e.g. crew, emperor, etc.). The male passengers are shown on the top as light blue pie slices. Show female passengers on the top as pink pie slices.
- **Task 4:** The red curves represent the high readings of the weather in three cities in a period of time. Show the low readings as blue lines.

7.4.5 Form

- **Survey Questions:**
  - To what extent do you agree with the following statements?

    The answer should be: I strongly disagree, I disagree, I neither disagree nor agree, I agree, or I strongly agree.

    - I am confident that my visualizations produce the expected outcomes described in the tasks
    - The inspector was helpful.
    - The tutorial was helpful.
    - The formulas were easy to understand.
  - How often did you use the inspector on average per task?
  - What difficulties did you encounter during the study?
  - Which parts of the formulas were difficult to understand for you?
  - Which parts of the formulas were easy to understand for you?
  - Do you have any suggestions for improvement?

- **Understandability Questions:**
  - Describe the effect of the "." element in the Uvis formulas.
  - Describe the effect of the "!" element in the Uvis formulas.
  - Describe the effect of the `"-<"` element in the Uvis formulas
  - Describe the effect of the "index" element in the Uvis formulas.

7.4.6 Results

Quantitative results: Figure 7.10 provides an overview of the quantitative results of the evaluation. In all tasks, participants in group A completed their tasks in a shorter time than participants in group B. Furthermore, participants in group A had better solution quality than participants in group B except for task 4 where there is no noticeable difference.

Qualitative results: The qualitative results can be summarized as follows:

- **Formulas**
  - All participants can learn basic SQL-like formulas.
  - All participants found basic mathematical formulas that refer to indexes easy to understand.
  - All participants roughly explained what a join formula `(-<)` means.

- Half the participants correctly explained what a dot (.) operator means.
- Only participant 1 correctly explained what a bang (!) operator means.
- Participants had problems understanding formulas defining the `SweepAngle` of a `PieSlice`. The formula was rather long and contained aggregate functions.

- **General observations**
  - In customizing a visualization, participants could draw analogies from existing parts, and build on new parts that are slightly different. This was obvious in tasks 3 and 4.
  - Participant 2 appreciated the fact that she viewed everything she needed (e.g. data, properties, form, etc.) when working on the tasks.
  - Most participants found it annoying that they could not compare the specifications of two visual objects side by side.
  - All participants ignored the error list.
  - All participants learned to use the data model.
  - Participants in group A found the inspector helpful and said it made them learn how to specify a visualization.
  - When asked after the end of each task about how confident they are about their solution, two participants in group A looked at the inspector first to check the visual mappings and answered "yes". The participants in group B were hesitant to say yes. Instead the answers were "I guess so" and "Maybe so".
  - Participant 6 thought the data was hidden, and that's why he could not check that his solution was correct. He did not have the inspector.

8

Conclusion and Future Work

This dissertation presented Uvis, a visualization system that targets savvy designers. With Uvis, designers drag and drop visual objects, set each visual object property with a formula, and see the result immediately.

The formulas are declarative and similar to spreadsheet formulas. The formulas compute the property values and can refer to fields, visual properties, functions, etc.

Cognitive aids assist designers while implementing a visualization. For instance, designers can check the correctness of their visualizations using the inspector.

Uvis produces visualizations that perform sufficiently.

Uvis formulas can express a collection of custom visualizations that are made of primitive and specialized visual objects.

In theory, Uvis is more accessible to savvy designers than existing visualization tools. A preliminary evaluation shows that savvy designers can learn the basics of Uvis.

8.1 Contributions

The thesis hypothesizes: *It is possible to express custom visualizations with Uvis spreadsheet-like formulas, and savvy designers can learn how to refine the custom visualizations.*

Substantiation of this hypothesis consists of the following contributions:

- The expressive power of formulas is substantiated with a collection of custom visualizations. The visualizations have various characteristics. For instance, some have a radial layout and others have a linear out. Using Uvis formulas, variations

of life lines (3), spiral graphs (1), horizon Graphs (39), circle views (38), tile maps (54), tree maps (55), indented trees, line charts, pie charts, and bar charts have been made.

Since Uvis formulas follow the spreadsheet paradigm, some interactive visualizations can be implemented with no or little event handling.

- To ensure that savvy designers can learn the Uvis approach, Uvis was iteratively designed based on feedback from savvy designers. This resulted in novel cognitive aids. As an example, upon specifying the `Rows` formula, Uvis automatically sets the Top and Left formulas. The visual objects cascade, and designers can see that multiple visual objects were created. As another example, the inspector shows the data behind the visual objects, and the sub-expression values. Usability studies show that these aids reduced usability problems.

- To compare the usability of Uvis with other tools, Uvis was compared with three other visualization tools using an example and using the cognitive dimensions of notations. The result favours Uvis as a tool for custom visualizations.

- To evaluate designer's performance with Uvis, a preliminary experiment was carried out with six savvy designers. The result is that they can learn the basic concepts of Uvis, and modify custom visualizations. Further, the inspector improved their performance.

8.2 Future Work

- **Port to other platforms:** Uvis currently supports desktop applications. The web is much more prevalent. We need Uvis to run on the web. However, this introduces challenges. Uvis applications need to integrate seamlessly with several web technologies: CSS for styling, JavaScript for data binding and interaction, HTML for web content, and so on.

  Porting to mobile platforms is also a must for the future.

- **Connect to other database systems:** At present we have only tested Uvis with MS-Access databases. We use .NETs ADO to access the database and in

principle it should work with other databases too, but we expect surprises. For instance, there are variations of SQL syntaxes depending on the database system.

- **Support non-tabular data:** Some data are not relational, for instance XML data, trees, graphs. We need formulas that can make these data sources look like relational tables.

- **More interactive visualizations:** We need to support more common interaction mechanisms such as fish-eye lenses, linking and brushing technique, semantic zooming, etc. We need to investigate the best way to support that, a visual object that hides implementation details and reduces customizability, traditional event handling, or somewhere in between?

  Furthermore, we need to support event handlers for keyboard, mouse and gestures. At present uVis handles only simple events such as `Click`.

- **Run pilot projects:** We need to run pilot projects with industry, for instance, with health-record vendors, software houses and hospitals. This will help us collect information about the kinds of problems savvy designers encounter in daily production.

- **Evaluate More:** The current evaluation relied mainly on modification tasks. Asking designers to create visualizations from scratch introduces new challenges. For instance, designers need to remember formulas, and they don't have existing components to compare with. This will help us identify more weaknesses and strengths of the Uvis approach.

  We also need to evaluate to what extent savvy designers can implement or refine interactive visualizations.

- **Investigate cognitive aids:** Some cognitive aids might improve ease of learning at the expense of task efficiency. Further, the usefulness of cognitive aids vary from designer to designer. These issues have to be investigated.

  The fourth phase of iterative design as well as the evaluation resulted in designers needing more cognitive aids. For instance, some designers needed to compare the specifications of two visual objects side by side. We need to investigate whether this aid is necessary, and whether more aids are needed.

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Appendix A

Usability Study Documentation

The appendix gives examples of hand-written documentation used for the usability study. For full and computerized documentation, refer to (51). For documentation of the evaluation study, refer to (53).

A.1 The Usability Log of Participant 1

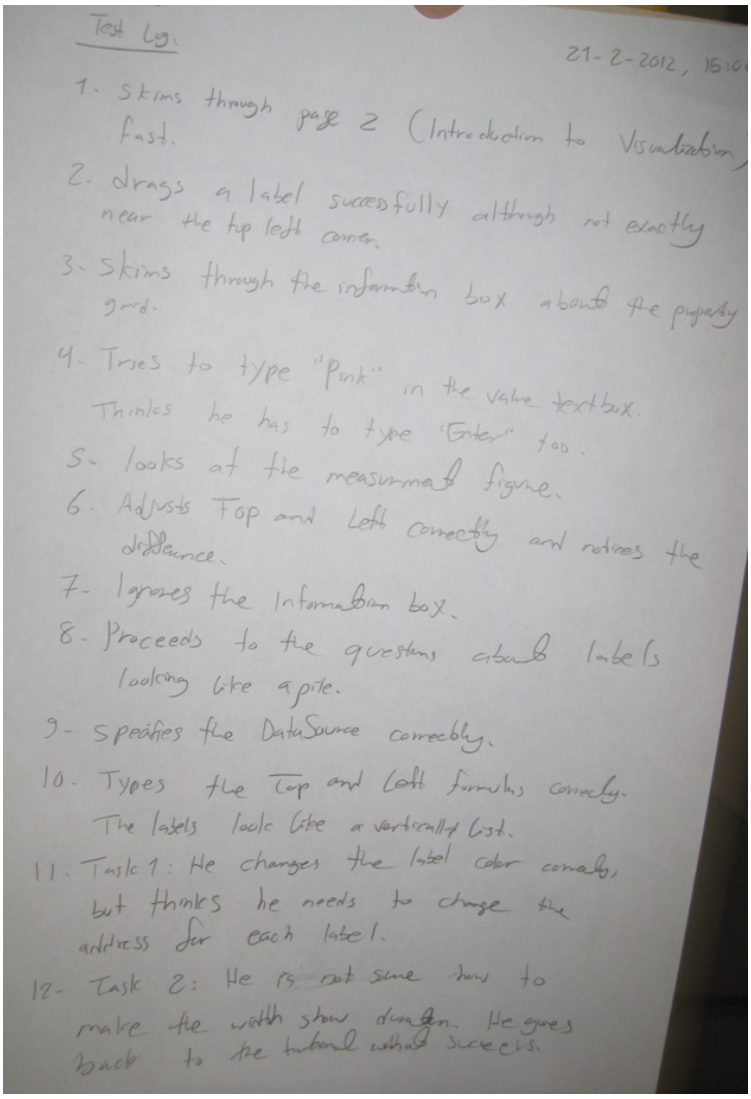
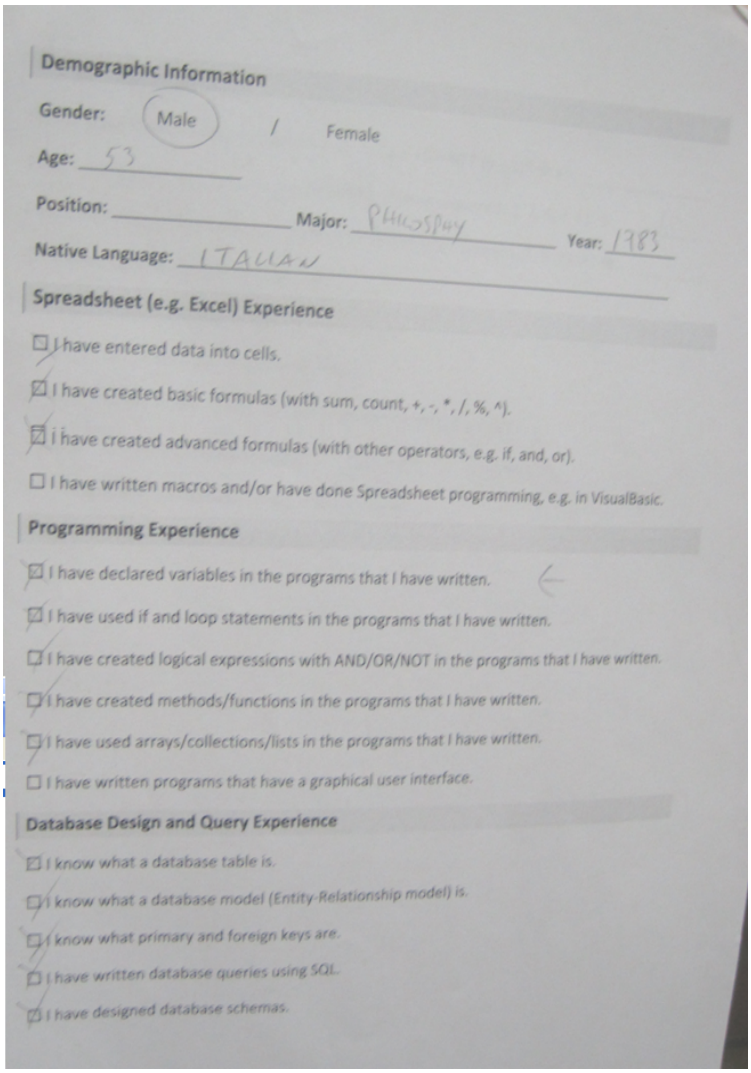


Figure A.1: A snapshot of the usability log of participant 1

A.2 The Background Form of Participant 10



Demographic Information

Gender: Male / Female

Age: 53

Position: _____ Major: Philosophy Year: 1783

Native Language: ITALIAN

Spreadsheet (e.g. Excel) Experience

- ☐ I have entered data into cells.
- ☑ I have created basic formulas (with sum, count, +, -, *, /, %, ^).
- ☑ I have created advanced formulas (with other operators, e.g. if, and, or).
- ☐ I have written macros and/or have done Spreadsheet programming, e.g. in VisualBasic.

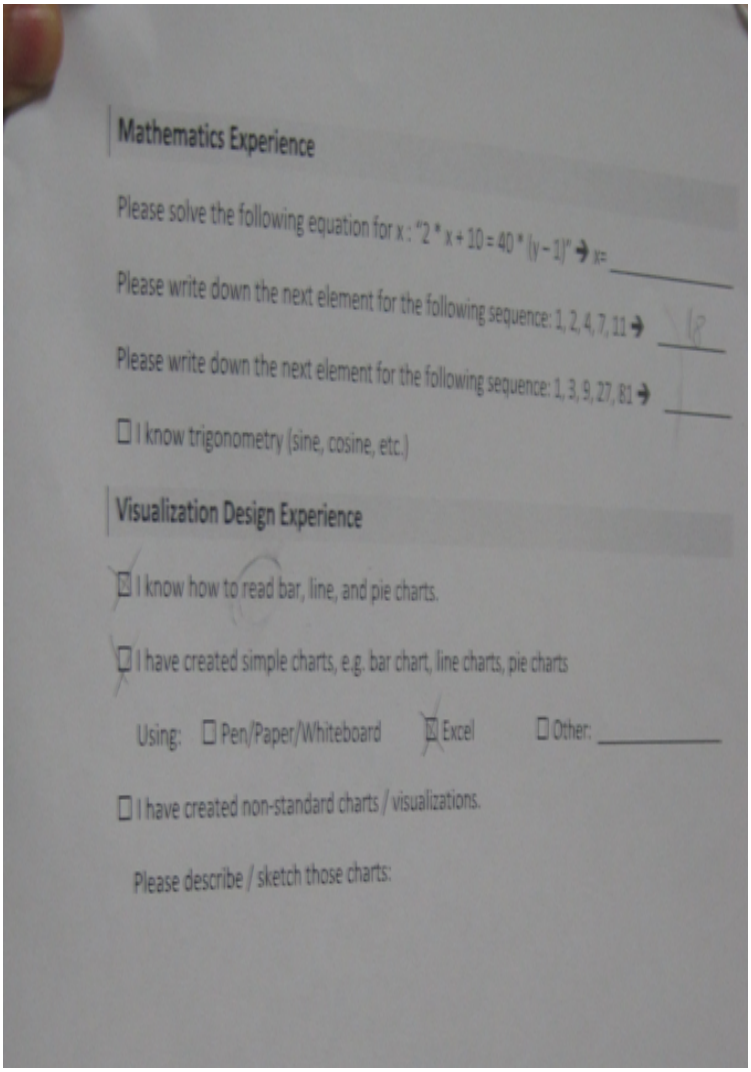
Programming Experience

- ☑ I have declared variables in the programs that I have written.
- ☑ I have used if and loop statements in the programs that I have written.
- ☐ I have created logical expressions with AND/OR/NOT in the programs that I have written.
- ☐ I have created methods/functions in the programs that I have written.
- ☐ I have used arrays/collections/lists in the programs that I have written.
- ☐ I have written programs that have a graphical user interface.

Database Design and Query Experience

- ☑ I know what a database table is.
- ☐ I know what a database model (Entity-Relationship model) is.
- ☐ I know what primary and foreign keys are.
- ☐ I have written database queries using SQL.
- ☐ I have designed database schemas.

Figure A.2: The background form of participant 10, part A



Mathematics Experience

Please solve the following equation for x: "2 * x + 10 = 40 * (y - 1)" → x= _____

Please write down the next element for the following sequence: 1, 2, 4, 7, 11 → 18

Please write down the next element for the following sequence: 1, 3, 9, 27, 81 → _____

☐ I know trigonometry (sine, cosine, etc.)

Visualization Design Experience

☒ I know how to read bar, line, and pie charts.

☒ I have created simple charts, e.g. bar chart, line charts, pie charts

Using: ☐ Pen/Paper/Whiteboard ☒ Excel ☐ Other: _____

☐ I have created non-standard charts / visualizations.

Please describe / sketch those charts:

Figure A.3: The background form of participant 10, part B

A.3 The Understandability Form of Participant 10

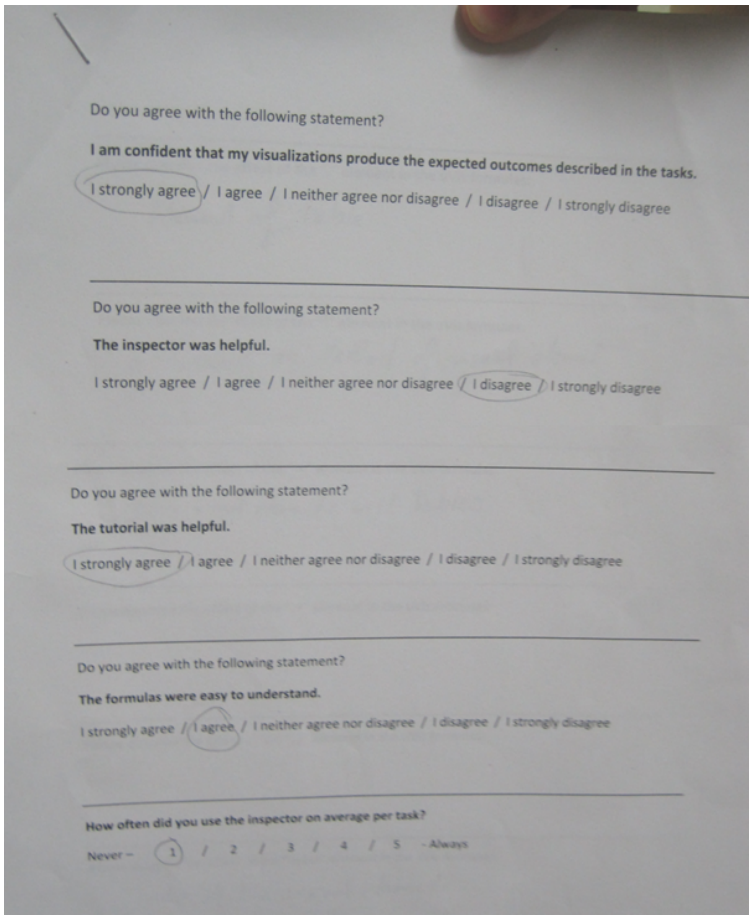


Figure A.4: The understandability form of participant 10, part A

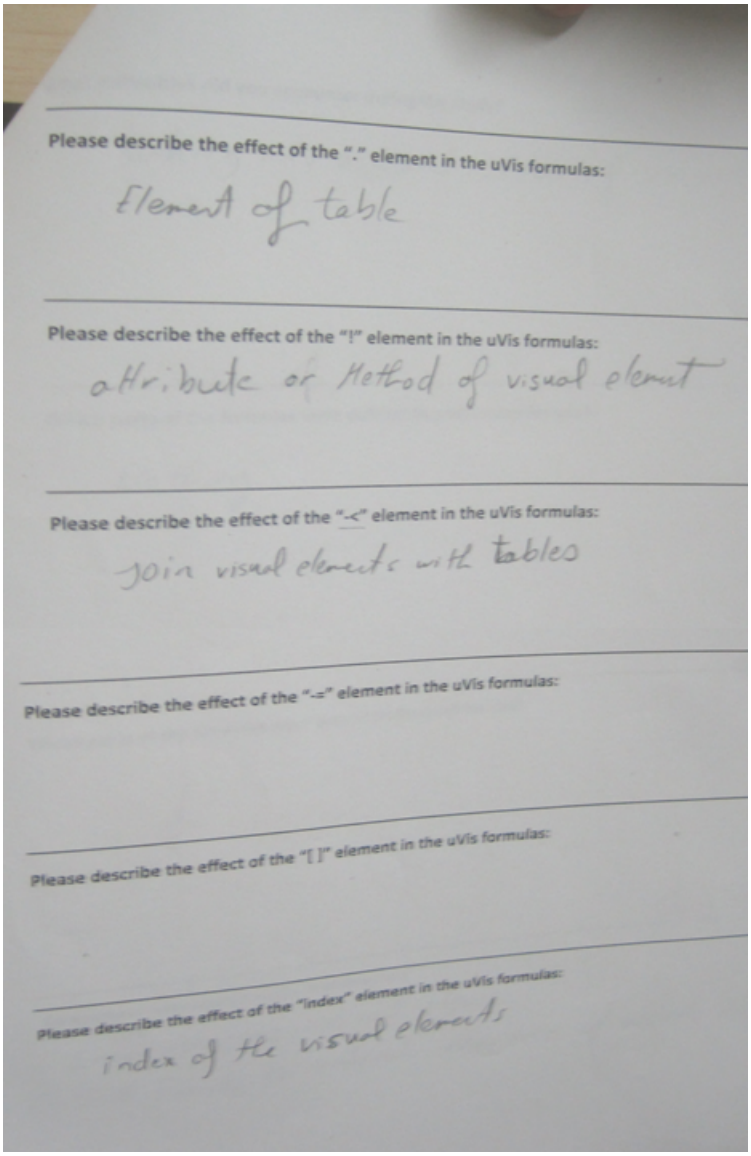


Figure A.5: The understandability form of participant 10, part B

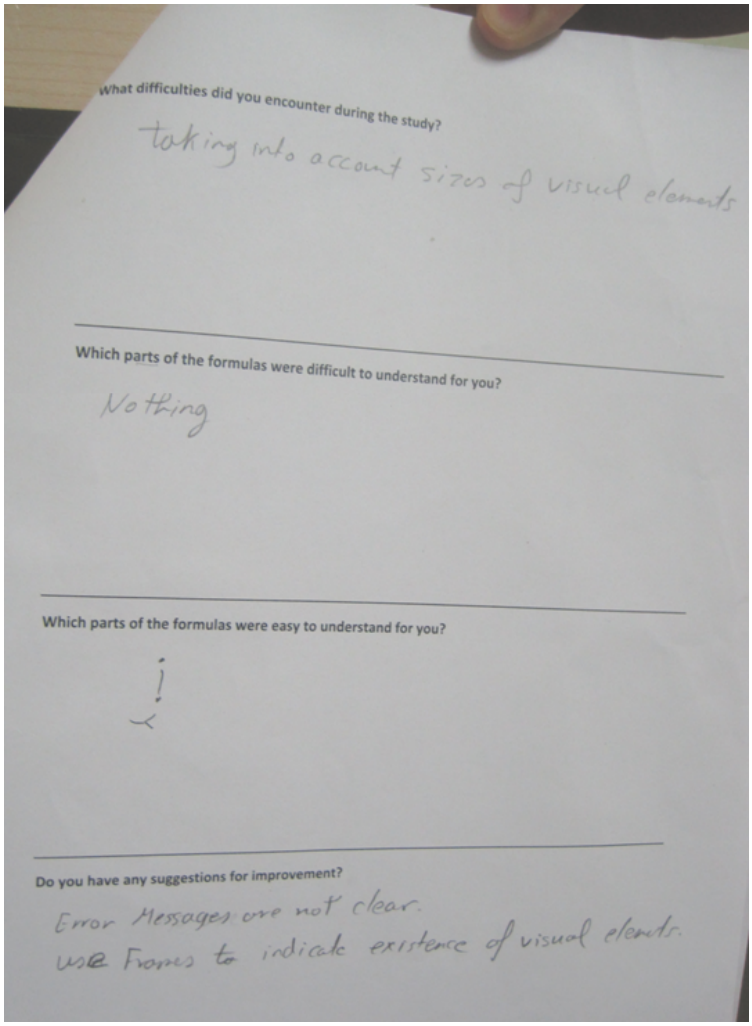


Figure A.6: The understandability form of participant 10, part C