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Depicting More Information in Enriched Squarified Treemaps with Layered Glyphs

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Abstract: The Treemap is one of the most relevant information visualization (InfoVis) techniques to support the analysis of large hierarchical data structures or data clusters. Despite that, Treemap still presents some challenges for data representation, such as the few options for visual data mappings and the inability to represent zero and negative values. Additionally, visualizing high dimensional data requires many hierarchies, which can impair data visualization. Thus, this paper proposes to add layered glyphs to Treemap's items to mitigate these issues. Layered glyphs are composed of N partially visible layers, and each layer maps one data dimension to a visual variable. Since the area of the upper layers is always smaller than the bottom ones, the layers can be stacked to compose a multidimensional glyph. To validate this proposal, we conducted a user study to compare three scenarios of visual data mappings for Treemaps: only Glyphs (G), Glyphs and Hierarchy (GH), and only Hierarchy (H). Thirty-six volunteers with a background in InfoVis techniques, organized into three groups of twelve (one group per scenario), performed 8 InfoVis tasks using only one of the proposed scenarios. The results point that scenario GH presented the best accuracy while having a task-solving time similar to scenario H, which suggests that representing more data in Treemaps with layered glyphs enriched the Treemap visualization capabilities without impairing the data readability.

Keywords: data visualization; evaluation; glyph; treemap

1. Introduction

The Treemap is an information visualization (InfoVis) technique that uses recursive areal subdivision to visualize hierarchical data organized in tree structures [1]. The areas are proportional to the data values: the higher the data value, the greater the area. One of the strengths of some Treemaps types is the space-filling aspect of the visualization, which uses the whole available display to convey information more efficiently than traditional tree diagrams [2]. There are different layout subdivision algorithms to subdivide the visual space into specific shapes, such as circular [3], rectangular [4], polygonal [5], squarified [6], geographical-like [7] and even hybrid approaches [8].

Two issues are essential when choosing one of those algorithms: layout stability and visual data readability, and choosing a trade-off between them is a critical point in designing a Treemap algorithm. The layout stability is the ability of small changes in data reflecting small changes in the layout, and visual data readability is concerned about the quality of the data representation. The readability is

better for shapes with a low aspect-ratio (e.g., rectangles closer to squares) because thin shapes make it challenging to see and compare the sizes of the items.

Despite that, Treemap still presents some challenges for data representation, such as the few options for visual data mappings and the inability to represent zero and negative values. Additionally, visualizing high dimensional data requires many hierarchies, which can impair data visualization. One possibility to overcome these issues is overlaying the Treemap with glyphs—visual representations that can depict data in its components [9]—but there is a lack of studies proposing and testing such an approach. Thus, considering the Treemap challenges, the potential of glyphs to represent multidimensional data, and the lack of studies and evaluations about glyphs in Treemaps [10], this work presents a prototype that adds configurable layered glyphs in visual Treemap items to mitigate the squarified Treemap challenges. With this approach, the Treemap can represent more multidimensional data, including options to encode small, zero, and negative values.

In this research, we propose layered glyphs—glyphs that use overlapped layers—where each layer encodes a visual variable that represents a single data dimension. The layers compose into multidimensional glyphs by making sure that all layers are readable, even when partially overlapped by other layers (See Figure 1). This choice of layered glyphs and squarified Treemap is a starting point to evaluate the combination of glyphs and Treemaps since both approaches have similar aspect-ratios (close to 1). The main contributions of this work are (1) to provide an InfoVis tool that implements this combination and make it available for download and use under the MIT License and (2) to evaluate the analysis scenarios where the combination of layered glyphs and squarified Treemaps can be useful.
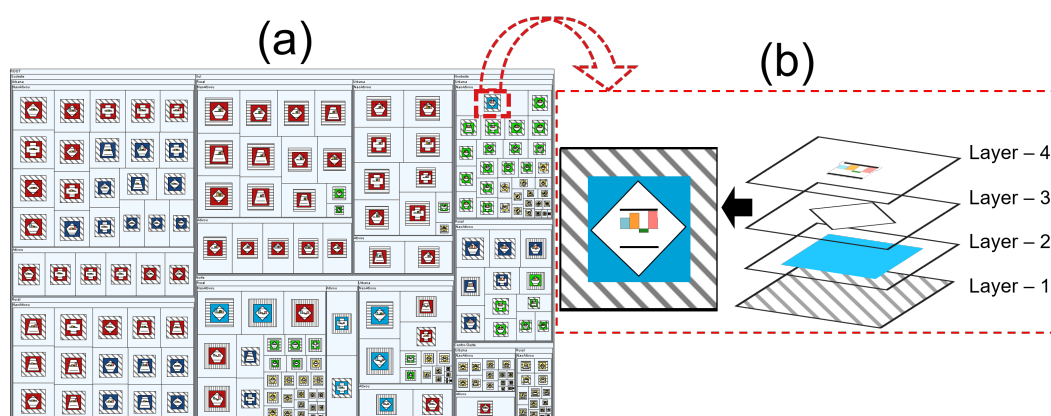

Figure 1. (**a**) A squarified Treemap with layered glyphs and (**b**) The adopted design strategy for the creation of layered glyphs, using overlapping layers, with each layer encoding a visual variable. The hierarchy of the Treemap maps three categorical dimensions, while the item's size maps a quantitative one. The layers 1, 2 and 3 map a single categorical or ordinal dimension each, and layer 4 is a profile glyph that can map up to eight quantitative dimensions.

For the evaluation, we tested three scenarios in a comparative analysis: Treemap with glyphs and without hierarchy (G), Treemap with glyphs and hierarchy (GH), and Treemap without glyphs and with hierarchy (H). We conducted a user study with 36 volunteers to evaluate the scenarios. Each participant performed eight user tasks using only one of the three visualization scenarios. Thus, we aim to measure the effect that adding glyphs to Treemaps has on the evaluated tasks in terms of task speed and accuracy.

The paper is organized as follows. Section 2 presents the background context, addressing topics such as information visualization, the Treemap technique, and glyphs. Section 3 shows related works. Section 4 presents the proposed prototype for this research. Section 5 presents the methodology of the user study. Section 6 shows the results. Finally, Section 7 presents final remarks and future works.

2. Background Context

This section includes some background on information visualization, Squarified Treemap, and glyphs. These concepts are applied in the proposed prototype; therefore, they are essential to comprehend the remainder of the paper.

2.1. Information Visualization

Information Visualization (InfoVis) comprises the study of visual representations and interactive techniques to explore abstract data, aiming to improve user's understandings about the data, patterns, outliers, and the relations between them. It is a field that studies visual techniques to strengthen perception, communication, and cognition about the data [11–13].

The main characteristics of visual mapping of an InfoVis technique are the spatial substrate, the graphical elements, and the graphical properties [14]. The spatial substrate is the layout of the visualization, the disposition of graphical elements on the screen. The graphical elements are the visual marks, such as points and lines that represent data entries, and the graphical properties are properties of graphic elements that are noticeable to the retina of the human eye.

Another relevant aspect of InfoVis tools is the dynamic interaction to support the data analysis, which enables the user to explore the data and pursue an answer. There are several ways of interacting with data, such as sorting, filtering, highlighting, aggregating, accessing detail on demand, adding visual mappings, re-expressing, zooming, and panning [12].

Shneiderman [15] suggests that an InfoVis tool should at least allow the users to perform overview, zoom, filter, and details on demand. Additionally, Shneiderman describes seven data types as the basis for classification of InfoVis techniques: 1D, 2D, 3D, Temporal, Multidimensional, Trees, and Networks.

2.2. Squarified Treemap

From the large number of techniques that visually represent hierarchical data [16], i.e., data in tree data structures, the Treemap [17] technique is one of the most popular [18]. The main reasons for its popularity are: provides a good overview of large datasets; the data hierarchy facilitates the comparison and identification tasks; the layout of the items facilitates the identification of the order between them [1].

The Treemap, in its original conception, subdivides the screen space recursively into nested rectangles to represent the hierarchical structure of the data, and each of them representing a node of the tree. The area of them is proportional to the value of the children nodes that compose it, and the layout algorithm uses the maximum visual space available to display the data [1,17].

The layout subdivision algorithm can use a variety of shapes, such as circular [3], rectangular [4], polygonal [5] or geographical-like [7]. One of subdivision algorithms is the Squarified Treemap [6] that tries to make the rectangles as square shape as possible. Thus, according to [6], square-like shapes provide a better visual comparison of items when their aspect ratios are similar, the most efficient use of display space and the visual elements are more comfortable to spot and point out.

However, the technique still presents challenges for data representation, particularly: few options for encoding visually the data (limited to size, color, and label); limited visual options of negative numbers, zero or missing data; and visual clutter caused by increasing the number of hierarchies.

2.3. Glyphs

In the context of InfoVis, a glyph is a visual representation of a data entity or a set of data, where its graphical properties (e.g., color, shape, size, etc.) map one or more attributes of a dataset [9]. This concept is a broad and general definition for a glyph, embodying an extensive range of types of glyphs created until now, including markers at a scatterplot, bars of a histogram, and even the line of a line chart [19].

Many authors published lists of visual variables more frequently used for mapping data values [20–22]. They included: position (1D, 2D or 3D), size (length, area or volume), shape, orientation, material (hue, saturation, intensity, texture or opacity), stroke style (width, dashes or opacity) and dynamics (movement speed, movement direction, and blinking rate).

According to Ward et al. [23] and Fuchs et al. [10], the predominant types of visual variables for mapping data into glyphs are:

- One-to-one: in which each different data attribute is mapping to one distinct visual variable type;
- One-to-many: use redundant mappings to improve precision and facilitate the data interpretation;
- Many-to-one: in which many or all data attributes map one common type of graphical feature, separated by space, orientation, or other transformation.

Fuchs et al. [10] and Ward et al. [23] presented some examples of glyph design and visual mappings, including: Star glyphs [24], Stick figures [25], Face glyphs [26], Tree glyphs [27], Box glyphs [28], Arrow glyphs [29], Autoglyphs [30], Profile glyphs [31] and Polygon glyphs [32].

In summary: this research applies layered glyphs to represent additional data to visual items of squarified Treemap technique, aiming to improve not only the representation of small, zero, and negative values but also increase the visual data dimensionality. We proposed glyphs for both categorical and ordered data. Each glyph layer can visually map data with color, shape, texture, text, and length; the layers compose into glyphs by associating each of these visual variables to a data dimension. Each layer is visualized partially, except for the top layer, allowing to perceive the visual variable values in each layer.

3. Related Work

Many research investigated ways to improve information representation in Treemaps by adding other techniques, for example: Treemap + Node-Links [33], Treemap + Table Lens [34], Treemap + Bar Charts [35], and Treemap + Choropleth [36]; However, the problems discussed in Section 2.2 remains open.

This work follows the same approach cited in the related papers, combines two visualization techniques, proposing to merge Treemap + glyphs techniques. This section presents two study categories that influenced this work: studies on glyphs applied in several InfoVis techniques, and studies about the use of glyphs specifically in Treemaps.

3.1. Glyph Studies

This section presents the glyph studies that provided the foundation of our proposal, such as design guidelines and configuration possibilities.

Fuchs et al. [10] published a systematic review involving 64 papers related to the use of glyphs in data visualizations. With their review, they intended to improve researchers understanding regarding the optimal design of glyphs to improve information gain. The study also pointed out open research scenarios in the literature, like the study of glyphs in Treemaps and other layouts. They also highlight the most used glyph designs and evaluation methods.

Borgo et al. [37] presented a state-of-the-art investigation focused on glyph-based visualizations; their review included considerations regarding the design and implementation of glyphs, as well as their application in different visualizations. They presented many evaluation studies about the perception of visual variables of glyphs, in which they reach a consensus that the most common pre-attentive variables in glyphs are order, color, size, shape, and orientation.

Ribarsky et al. [38] implemented Glyphmaker, a tool to ease glyph creation for non-specialist users. Glyphmaker allows users to personalize graphical properties by using a simple glyph editor and a point-and-click binding interaction. The tool gives flexibility and dynamism to the user in the task of glyph creation.

Theron et al. [39] presented a tool which runs multiple InfoVis techniques, including parallel coordinates, Treemaps, and glyphs. Their study focused on the recovery of cinematography data. They used shape-based glyphs, varying the shape to represent the person profile involved in a movie.

In their glyph design, the overlapping of the shapes never causes total occlusion. We highlight this positive characteristic of their design, and we took as an inspiration for our proposed glyph design.

Maguire et al. [40] proposed a systematic process for glyph design exploring both the concepts of data hierarchy and the ability to distinguish visual variables through the overlapping of them. Their work was applied in the biology field to visualize of projects and experimental processes.

Legg et al. [41] presented a visualization solution for the analysis of sports performance data in real-time. The authors used a glyph design to allow the training team and analysts to visualize actions and events at a glance. The article presented a glyph comprised of seven attributes, both categorical and ordered. A pictogram represents the glyph's key event, and its design features the overlapping of visual variables without harming the reading of the glyph.

Another application is Glyph Sorting [42]. The research used glyphs to enhance sport event analysis, which uses the scatterplot visualization. The glyphs replace the scatterplot dots by a circular shape and can map up to nine attributes. A pictogram in the center of the circle represents the events of the match. Their glyphs also used the overlapping of visual variables without undermining the understanding of the data it represents.

3.2. Using Glyphs in Treemaps

Khan et al. [43] conducted research centered at focus+context visualization, motivated by the need to visualize query results of a large filesystem in a Treemap. The result (the "focus") of a query used glyphs above a squarified Treemap items (the "context"), causing partial occlusion of them. The glyph's design represents four attributes: three categorical and one quantitative; however, the user can not modify the design of the glyph.

Fischer, Fuchs, and Mansmann [44] developed an application to visualize large network traffic data, focus on subnets traffic. Therefore, they used a circular Treemap layout with a circular glyph representing 24 h, where each circular segment indicated 1 h of a subnet or an IP address. Also, they use color to indicate the amount of network traffic in bytes. Their design also employed a static structure that did not allow modifications of the glyph.

Elmqvist and Fekete [45] proposed the use of profile and pie glyphs to represent items aggregation, aiming to improve the understanding of visualizations. The authors' investigation resulted in a set of guidelines for the design of glyphs.

Soares et al. [46] presented a merge proposal of a squarified Treemap and glyphs techniques to analyze multidimensional data. The glyphs were also dynamic since they enable the user to map data attributes, visual variables, and layers. Their work also suggested the use of an adaptive glyph that uses a decision tree to eliminate layers that are not visibly suitable due to the small size of the glyph. Even though the adaptive glyph can deliver information to the user even in Treemaps items with a small area, their glyphs only map categorical and ordinal attributes without any visual variable to represent quantitative data. Therefore the paper does not solve some challenges concerning negative numbers, zero or missing data representation. Additionally, the study does not address a user test aiming to indicate the efficiency and the efficacy of using adaptive glyphs in a squarified Treemap.

In summary: between the related works selected, which merge Treemap and glyphs, no one of them attacks all problems, mainly considering the representation of zero, negative, and small values. Besides, just a few papers conducted user studies to evaluate de glyph application on squarified Treemap. Other highlight characteristics are the use of glyph in overview visualization or after the filter usage. Table 1 summarizes the main differences between related approaches and our proposal.

Table 1. Proposals that used glyphs and proposals that used glyphs in treemaps compared with our approach.

	[38]	[39]	[40]	[41]	[42]	[43]	[44]	[45]	[46]	Our Approach
Uses glyph in the overview	X	✓	✓	✓	✓	X	✓	X	✓	✓
Increases amount of dimensions	✓	✓	✓	✓	✓	✓	✓	X	✓	✓
Number of visual variables	3	1	2	6	8	4	2	1	4	5
Uses squarified Treemap	X	X	X	X	X	✓	X	X	✓	✓
Glyph uses overlay	X	✓	✓	✓	✓	X	X	X	✓	✓
Uses quantitative glyph	✓	X	X	✓	✓	✓	✓	✓	X	✓
Uses categorical glyph	✓	✓	✓	✓	✓	✓	X	X	✓	✓
Glyph is domain-agnostic	✓	X	X	X	X	X	X	✓	✓	✓
Uses Treemap layout	X	X	X	X	X	✓	✓	✓	✓	✓
Had user studies	X	X	X	X	X	✓	X	X	X	✓

X → No; ✓ → Yes.

4. Prototype

In this section, we present the prototype developed to merge the techniques squarified Treemap and glyph. We explain the design of the proposed glyph, the functionalities of the prototype, and the prototype's process flow.

4.1. Glyph Design

The proposed glyph is a square-based shape and composed by layers. For the representation of categorical and ordinal attributes, each layer maps to a visual variable, which can be texture, shape, color (hue and brightness), and text. The values of the visual variables used in the glyph's layers and the data type that they are suited to represent are presented in Figure 2.
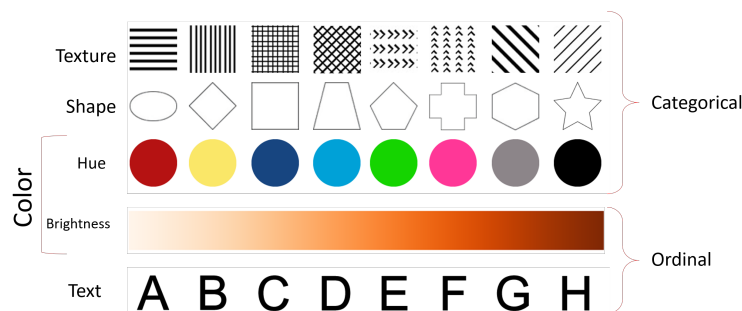

Figure 2. The values used in this study referred to the visual variables (layers): texture, shape, color hue, color brightness and text .

All glyph layers are aligned with the center of the Treemap item. Considering a layer N positioned above a layer N-1, the upper layer N overlaps N-1 by 65% to avoid total occlusion (See Figure 3). According to Soares et al. [46], 65% of overlap is a suitable threshold to perceive all layers. The position of the layers is fully exchangeable, and the user has the freedom to choose visual variables to represent the data for each of them, assembling a customized glyph that better fits the data analysis.

For example in Figure 3a the order (bottom-up) of layers are color, texture, shape, and text; In Figure 3b there was an exchange between texture and color.
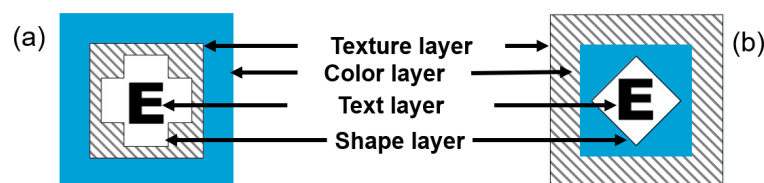

Figure 3. Layered glyph's design. (**a**)—A glyph with the visual variables: color, texture, shape, and text; (**b**)—In this glyph, color and texture were exchanged compared to (**a**).

To represent quantitative data, we consider the use of the profile glyph—a glyph to represent n-dimensional observations with n bars [23]—in the upper layer of the proposed glyph. The height of the bars is proportional to the data values selected, and the bars are next to each other [31]. In our project, the profile glyph is a particular type of layer that encodes quantitative information with a bar-chart miniature. Since any overlap may impair the understanding of the profile glyph, it is always positioned at the top-level layer to be fully visible.

The user might encode many quantitative dimensions to a profile glyph layer using bars. The use of colors is to facilitate the distinction between the data dimensions in the profile glyph. The user can add up eight dimensions (thus eight colored bars). The prototype may add more than eight bars, but its visibility may be impaired because of the Treemap item area. Profile glyphs may benefit from additional research to quantify its efficacy in different screen spaces, but that topic is out of the scope of this research. The length of the bars shows the normalized values of the data point in the associated dimensions.

The profile glyph allows the mapping of negative values, using an inverse bar that starts at the origin and grows down. Reference lines mark the minimum and maximum lengths that the bars can reach. We decided to use this reference lines so the user has a reference when comparing each profile glyph. Before plotting it the data was normalized since each Treemap item does not have the same size or area. Figure 4 presents an example of a layered glyph with three layers (visual variables), with the last layer—layer N—having a profile glyph with each bar representing a quantitative data dimension.
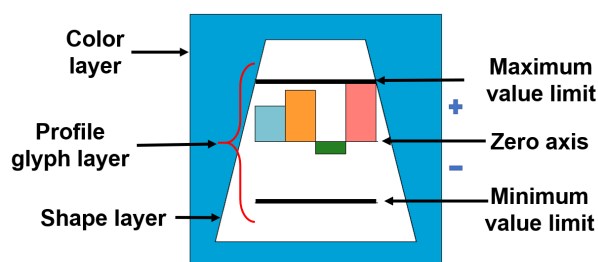

Figure 4. A layered glyph with three layers. The top layer presents a profile glyph, which represents quantitative data of four dimensions. The bars indicate positive values (above the zero axis) or negative values (below the zero axis), always respecting the reference lines that indicate the maximum and minimum size of the bar.

4.2. Treemaps with Layered Glyphs Tool

We implemented a tool to visualize multidimensional data in a squarified Treemap with layered glyphs, and it is available for download (Available at: http://labvis.ufpa.br/treemapglyphs). User studies are presented in the next section using it. The tool has the following main functionalities:

- Load a dataset;
- Configure and visualize the Treemap visual variables;
- Configure the glyph layers;
- Details on demand visualization.

As a first step to use the tool, the user has to select the data to be analyzed (a text file or a database view) and configure the initial visual mappings for the Treemap. After that, the user can add glyphs to the visualization, set up the order of the layers, and set the data dimensions mapped to the visual variables (See Figure 5).
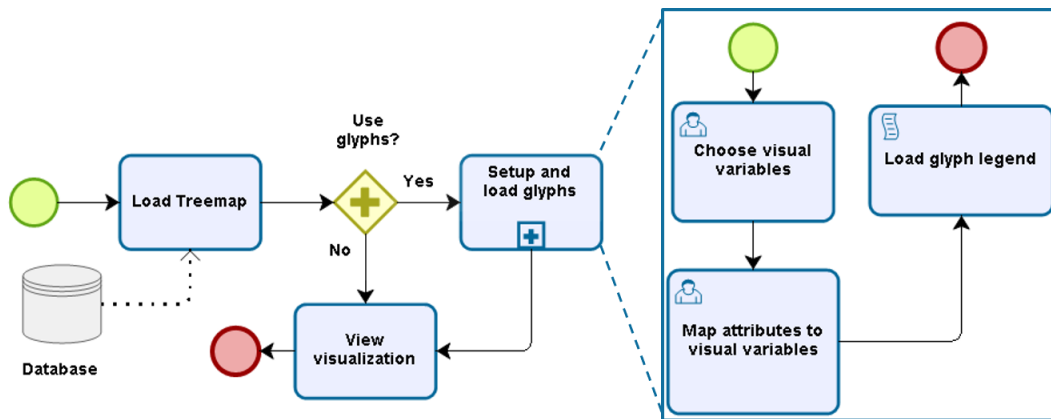
Figure 5. Prototype's process flow.

Figure 6a shows a print-screen of the Treemap technique overview with the addition of layered glyphs. To configure a glyph with categorical data, the user interacts with a list of visual variables: texture, color, shape, and text (See Figure 6b). The user can choose which of them will be used in the glyph composition, as well as define the presentation order of the layers.

After selecting the visual variables and their order, it is necessary to map the layers to the dataset dimensions (See Figure 6c). A menu shows a list of the available data dimensions for each chosen visual variables. After completing the glyph configuration, they will appear at the Treemap items. The tool also shows a legend for the visual mappings (See Figure 6d).

The glyphs can also represent quantitative data through a profile glyph in the most top layer (See Figure 7a). The tool shows a menu with a list of available quantitative data dimensions, and the user can select up to eight data dimensions into the profile glyph layer. The user can also alter the horizontal order of the bars if desired (See Figure 7b). A color legend helps to identify the dimensions mapped in each bar. (See Figure 7c).
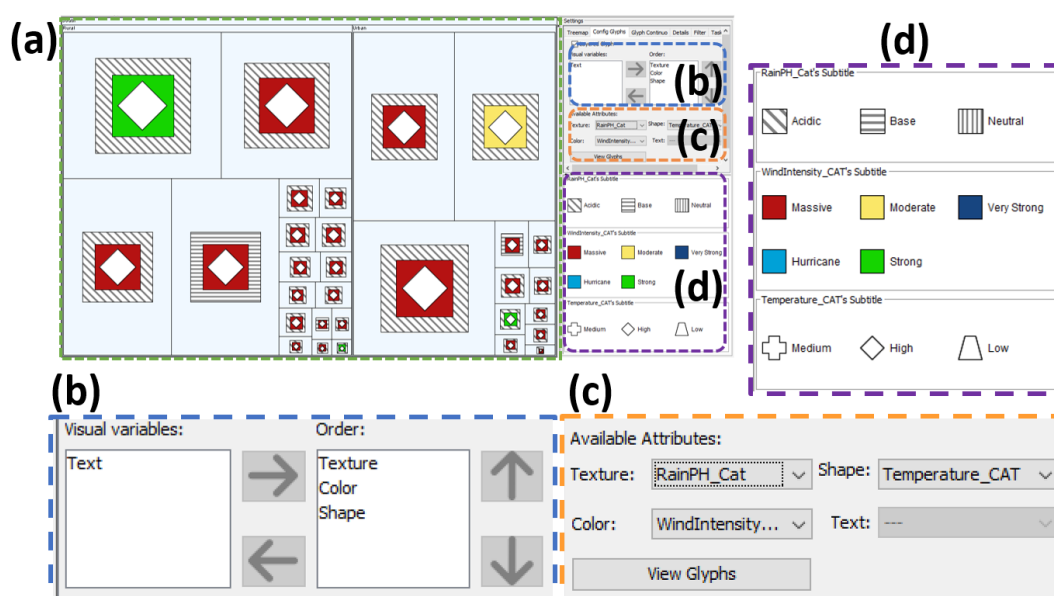

Figure 6. (**a**)—Overview of the prototype composed by Treemap and glyphs; (**b**)—Glyph's visual variables configuration area; (**c**)—Visual variables mapping area of the attributes; (**d**)—Presentation area of the glyph's legend.
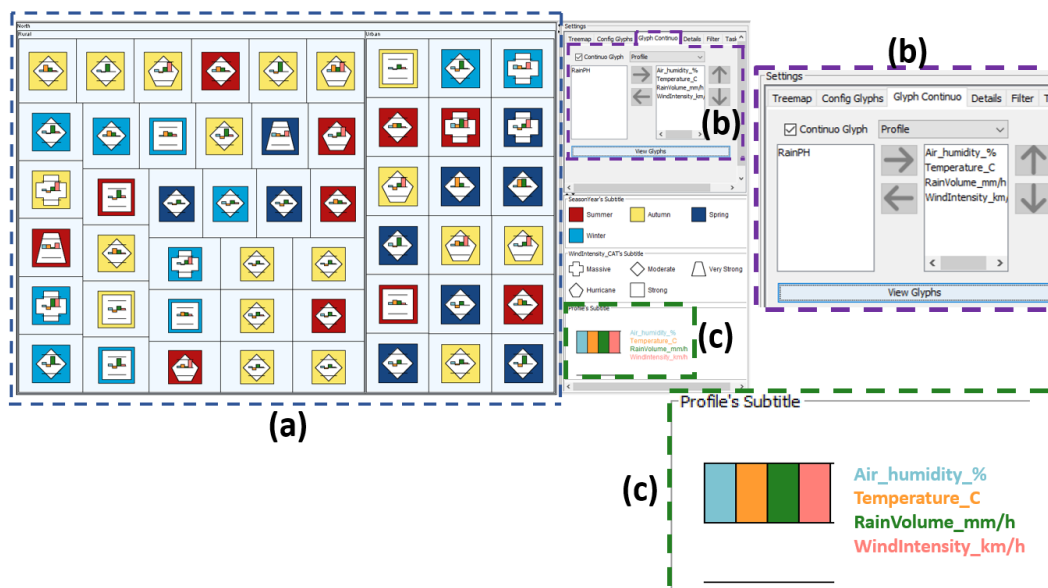
Figure 7. (**a**)—An overview of the treemap with quantitative glyphs and hierarchy. (**b**)—Profile glyph dimensions configuration. (**c**)—Profile glyph legend.

5. User Study

We have conducted a task-based user study to investigate the effectiveness (accuracy and task completion time) of layered glyphs embedded in Treemap items. The glyphs can increase data dimensions visually represented beyond those offer by the visualization technique, without impairing the reading of information presented on it.

In a bit more detail, we aim to evaluate if adding glyphs in Treemap items increases user performance during the search and data analysis tasks. For that, we have proposed a comparison between Treemap scenarios with and without glyphs for performing the tasks. Moreover, we aim to investigate if the proposed glyphs mitigate the visual clutter that occurs when using too many hierarchies and if it is suitable for negative, null, and small values representation.

The next sections will present important information about the user study such as the computational environment, the profile of participants, the used dataset, the hypotheses which guide the experiment, examples of test scenarios, user tasks applied, and procedures.

5.1. Computational Support

The testing room had a computer desk, two chairs, a monitor, and a notebook. The notebook used in the test has an Intel Core i7 processor and 8 GB of RAM, with its video output being a 21" monitor with 1920 × 1080 pixels of resolution. The center of the screen was positioned between 60 cm and 70 cm straight ahead from the participant's eyes.

5.2. Participants' Profile

A total of 36 volunteers with knowledge about InfoVis techniques participated in the tests, with ages ranging from 18 to 42 years old, between men (33) and women (3), graduates (31), and undergraduates (5) in the information technology area. For this research, we defined InfoVis experience as having enough knowledge to use and understand hierarchical techniques, such as participants that have previously coursed an InfoVis course in graduation or post-graduation, or have been InfoVis researchers for at least six months.

5.3. Dataset Description

A synthetic database with 200 entries and 13 attributes—five quantitative and eight categorical—was used in the evaluations (See Table 2). The main reason to use a synthetic dataset is the ease of controlling data characteristics for the test scenarios—for instance, scenarios with one or more unique answers, patterns or outliers. Thus, well-known visualization tasks [47,48] can be used for analyzing or exploring datasets.

Table 2. Dimensions of the synthetic weather dataset.

Dimension	Data Type	Data
SeasonYear	categorical	spring, summer, autumn, winter
Region	categorical	north, northeast, midwest, southeast, south
RainPH	quantitative	0 to 14
Air humidity%	quantitative	1 to 70
Temperature_C	quantitative	−15 to 35
Temperature_CAT	categorical	low, medium, high
Locality	categorical	rural, urban
RainVolume_mm/h	quantitative	1 to 30
WindIntensity_km/h	quantitative	1 to 120
WindIntensity_CAT	categorical	moderate, massive, hurricane, strong, very strong
CivilDefenseWarn	categorical	activated, non-activated
RainPH_Cat	categorical	acid, base, neutral
RainIntensity	categorical	weak, moderate, strong, very strong

It is essential to highlight that, although the synthetic dataset is about weather data, we focus only on the data structure; the semantics of the data (names of dimensions and attributes) are there only to facilitate the elaboration and communication of the tasks to the users. Thus, our study did not aim to simulate any real weather scenarios, and that fact was explicit mentioned to the participants before the tasks. Table 2 shows details of the dataset dimensions and their values.

5.4. Hypotheses

The main scenarios proposed for the evaluation have the Treemap as a background and consider the usage or not of hierarchies and layered glyphs, or include the combined usage of them. We expect that each type of scenario will have its advantages and disadvantages, and we intend to find answers for these expectations evaluating the following hypotheses:

Hypothesis 1. (H1). *Replacing Treemap hierarchies by layered glyphs improves user performance for performing search tasks.*

Hypothesis 2. (H2). *Combining Treemap hierarchies with layered glyphs improves user performance in search tasks when compare to Treemap with hierarchies only.*

Hypothesis 3. (H3). *Combining profile glyphs with Treemap hierarchies improves user performance for identifying negative values when compare to Treemap with hierarchies only.*

Hypothesis 4. (H4). *Combining profile glyphs with Treemap with hierarchies improves user performance for identifying the zero values when compare to Treemap with hierarchies only.*

Hypothesis 5. (H5). *Combining layered glyphs with Treemap hierarchies improves user performance for searching a single value compare to Treemap with hierarchies only.*

Hypothesis 6. (H6). *Combining profile glyphs with Treemap hierarchies improves user performance for identifying patterns in a data group compare to Treemap with hierarchies only.*

5.5. Test Scenarios

We defined three test scenarios to evaluate the effectiveness of the glyphs usage in Treemaps, according to the defined hypotheses:

- Scenario **G**: Treemap with **glyphs** and without hierarchy (See Figure 8);
- Scenario **GH**: Treemap with **glyphs** and with **hierarchy** (See Figure 9);
- Scenario **H**: Treemap without glyphs and with **hierarchy** (See Figure 10).

We proposed Scenario G to analyze cases in which glyphs replace all Treemap hierarchies. The GH scenario evaluates the usage of glyphs and hierarchies together in the Treemap. Finally, scenario H is the traditional usage of squarified Treemap with hierarchies without glyphs, as a baseline to compare the results with other scenarios.
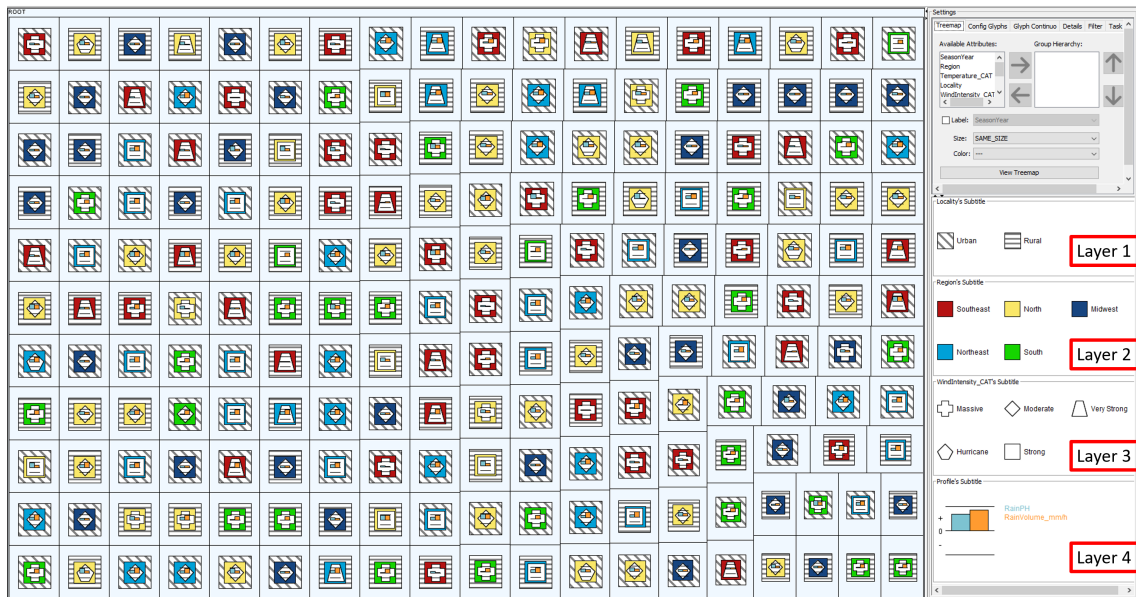

Figure 8. Scenario Glyphs (G) visualization configured for one of the user tasks. This visualization uses no Treemap hierarchy; the absence of hierarchy is replaced by categorical glyphs.
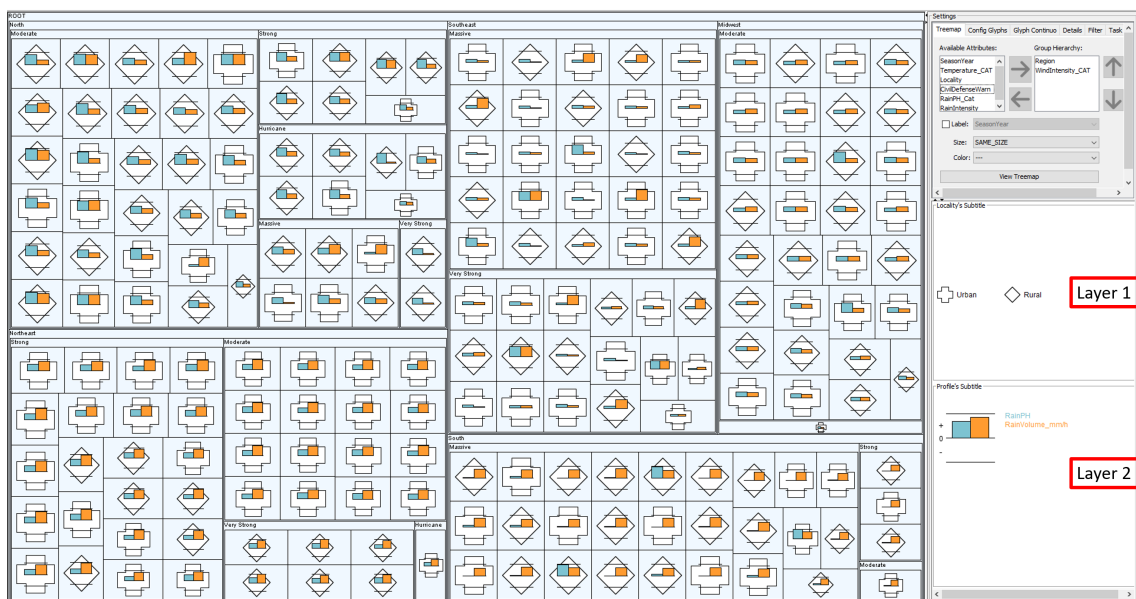

Figure 9. Scenario Glyphs and Hierarchy (GH) visualization configured for one of the user tasks. This visualization is a Treemap with hierarchy and complement.
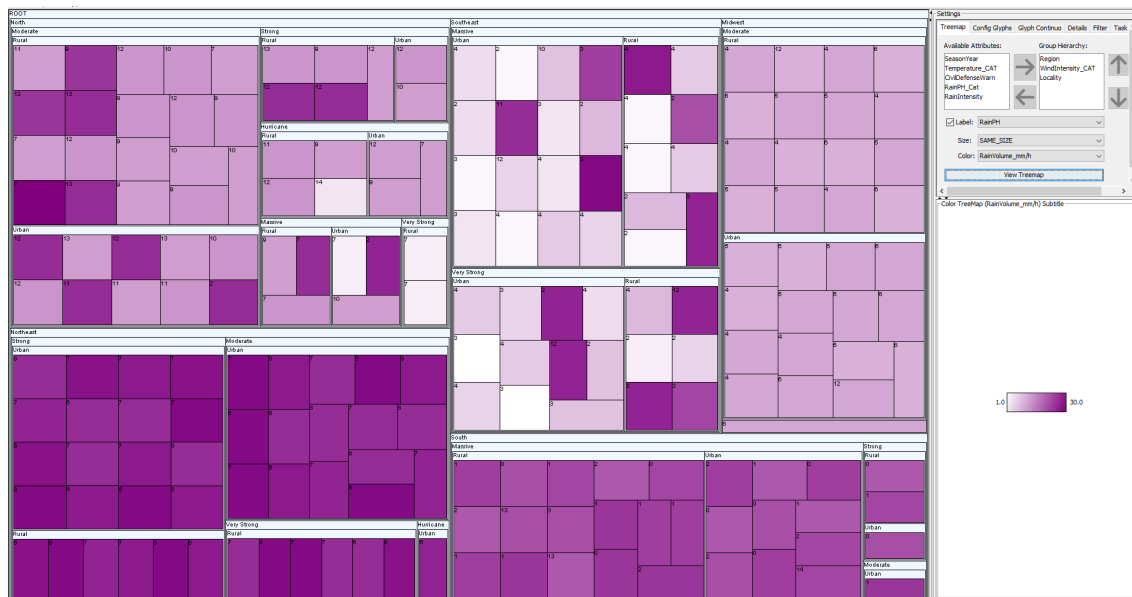
Figure 10. Visualization of Scenario Hierarchy (H) visualization configured for one of the user tasks. This visualization is a squarified Treemap with no glyphs.

5.6. User Tasks

We designed eight user tasks to support the analysis of the proposed hypotheses. Table 3 shows a description of the tasks, which hypotheses are related to, and explains for each task what it intends to be evaluated.

Table 3. List of tasks used in the evaluation.

Tasks	Discussed Hypotheses	What Is Being Evaluated?
T1—Locate the region where a basic rain record occurred, with massive winds, and had the civil defense alert activated.	H1, H2, H3, H4, H5, and H6	The use of glyphs to replace hierarchies.
T2—In the northern region, during the summer, select the three highest wind intensities.	H2	The facility to locate the highest values.
T3—In the Northeast region, select the record (one only) with a negative temperature.	H3	The facility to locate the negative values.
T4—Select the unique record in the south region for the rain with zero PH, strong winds and rural location.	H4	The facility to locate the zero values.
T5—Locate the region that registered only one occurrence of a hurricane.	H5	The facility to locate the unique value.
T6—Locate the region which has only one record of acid rain and low temperature.	H5	The facility to locate the unique and small value.
T7—Identify the wind intensity pattern for the rural location of the midwest region.	H6	The facility to identify patterns.
T8—During the spring, identify the region which has the lowest average air humidity. (%).	H6	The facility to identify and compare patterns between groups.

Each type of scenario has pre-configured visual mappings for each task. The visible attributes are consistent through all scenarios, i.e., they are the same data attributes using different visual mapping such as hierarchy, shape, color, etc. To illustrate the use of the same data attributes in all scenarios, consider the visual mapping for each of them in the Table 4 related to the task 4 of Table 3 for Scenario G (Figure 8), Scenario GH (Figure 9), and in Scenario H (Figure 10).

Table 4. Attributes distribution in the scenarios G, GH, and H on realizing the task 4. The user task used the same attributes, differing on the use of visual mapping.

Visual Mapping	G	GH	H
Treemap Size	—	—	—
Treemap Label	—	—	RainPH
Treemap Color	—	—	RainVolume_mm/h
Treemap Hierarchy	—	Region, WindIntensity_CAT	Region, WindIntensity_CAT, Localion
Glyph Texture	Localion	—	—
Glyph Color	Region	—	—
Glyph Shape	WindIntensity_CAT	Localion	—
Glyph Text	—	—	—
Profile Glyph	RainPH, RainVolume_mm/h	RainPH, RainVolume_mm/h	—
Total attributes used	5	5	5

5.7. Procedures

This section describes the procedures to conduct the tests. First of all, a set of people received an invitation to participate in the evaluation procedure by e-mail or social network. All the participants who accepted the invitation were volunteers, and they did not receive any fund compensation for that. Each participant undertook the test individually. Before the beginning of the tests, the conductor of the procedure informed the participant that the use of data collected during the tests would be anonymous. Besides that, if they wished they could stop the test at any moment, and there would not be a time limit for the execution of the tasks.

After that, the conductor showed a training video. The usage of a video was important to standardize the participants' training. The video included the following topics:

- a brief explanation of Treemap and glyph techniques;
- the design of the proposed glyphs;
- an overview of the used dataset;
- examples of tasks, similar to those of the test, but using a different synthetic dataset;
- information about how participants would provide the answers (e.g., clicking in a Treemap item).

After the training video, we presented preliminary InfoVis tasks with a different dataset. We highlight that the tests only started when the participant correctly answered at least two tasks at the preliminary step: one task containing quantitative data and another one containing quantitative and categorical data. Also, the participants had to reassure to the test conductor if they were already prepared to undertake the test.

When the user starts the test, a type of scenario (G, GH, or H) is randomly chosen, respecting the maximum of 12 participants per group without repetitions. Thus, all 36 participants formed three groups of 12, one group for each visualization scenario.

Each participant performed eight tasks—from T1 to T8—using only the visualization of the group (G, GH, or H) which the participant was associated with, i.e., no participant performed tasks in more than one scenario type. We pre-configured all visualization scenarios to guarantee the equivalency between them. Thus, participants did not need to configure the visualization scenarios, so they could focus on analyzing the visualization and finding the answer.

Since the only difference between the scenarios (i.e., the independent variable) is the presence or absence of glyphs or hierarchies, the effect can be measured. In the study, we collect data regarding time, error, and interaction, and this process is automatic in the tool. The participant only has to click on the Treemap items to answer a task, so all data is recorded. No information is collected from the training phase, as its purpose is only to make sure that participants are on the same knowledge level.

During the training and tests, only one conductor and one participant were present in the room. We shown the tasks at the top area of the user screen, immediately above the visualization (See Figure 11).
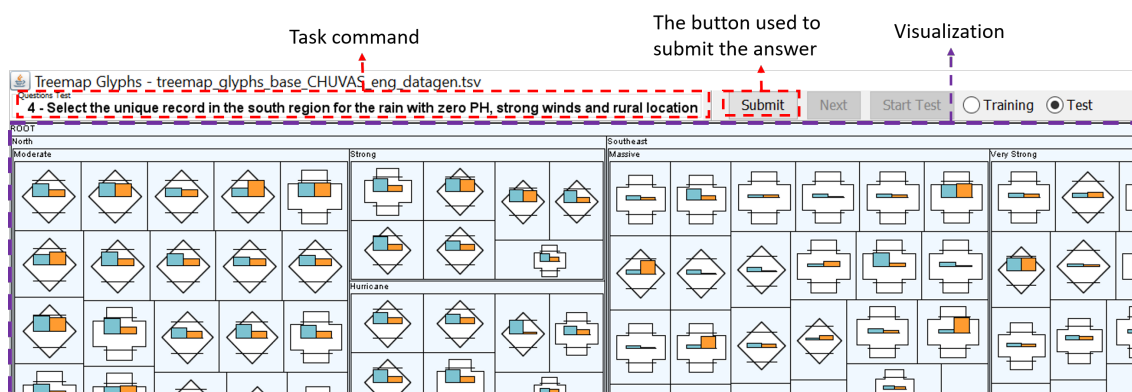
Figure 11. Example of task displayed to the participant, the task command and the submit button is above the visualization.

For the test, the participants performed eight tasks in a random order. They could only move to the next task after answering the current one. A participant starts a task clicking on the start button, and read it out loud, thereby the participant is free to understand the task request and begin to analyze the visualization. After that, the participant provides an answer by clicking on the Treemap item(s) and then on a submit button. The prototype saves the time between the start and submit buttons and also the participant's answer in a log file. After repeating this process for all the eight tasks, the test session is over.

6. Results

We analyzed three aspects of the collected data to compare the performance between the groups: the proportion of correct and wrong answers, the average response time with confidence intervals, and a pair-wise time effect size analysis [49,50]. Figure 12 shows how to interpret the charts that will present such aspects in the following sections.

Figure 12a shows the amount of correct and incorrect answers of 12 participants for one task in each scenario, and a pair-wise test using bootstrapping to compute the 95% confidence interval of the difference between each pair of groups. Figure 12b shows the mean response time of 12 participants and its 95% confidence interval, both for the same task. If the confidence intervals of the two groups are far apart, then there is a significant difference between them. For instance, in Figure 12b, there is no significant difference between H-GH, but there is between GH-G and H-G.

The Figure 12c shows the pair-wise time comparison between groups. We used bootstrapping [51] to compute the 95% confidence interval of the difference between each pair of groups. If the interval crosses zero, we can not reject the (null) hypothesis that the groups are equal. If the interval does cross zero, then we can reject the null hypothesis in favor of the (alternative) hypothesis that one group is better than the other (at $\alpha < 0.05$). Besides, Figure 12c shows the effect size in terms of Cohen's d [52] using a multi-colored bar that is positioned at the center and grows towards the faster scenario. The colors indicate the thresholds of Cohen's d effect sizes (insignificant, small, moderate, and large effect). Thus in Figure 12c, scenario GH is at least 38 s faster than scenario G, which is a large effect size (the 38 s mark reaches the dark-blue color).
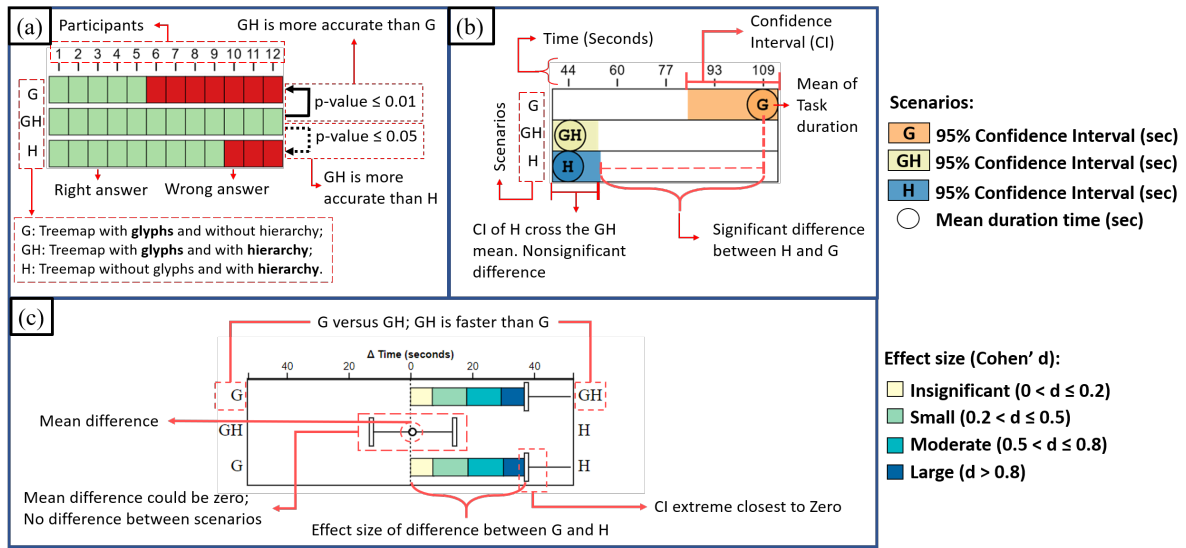
Figure 12. How to interpret the charts for the results of one task in the following sections. (**a**)—Quantity of correct and incorrect answers and a pair-wise test using bootstrapping; (**b**)—Mean response time with 95% confidence intervals; (**c**)—Pair-wise time comparison using bootstrapping and Cohen's d.

Figures 13 and 14 present the accuracy and time results of the tasks performed by all groups of participants, including the pairwise statistical analysis between groups.
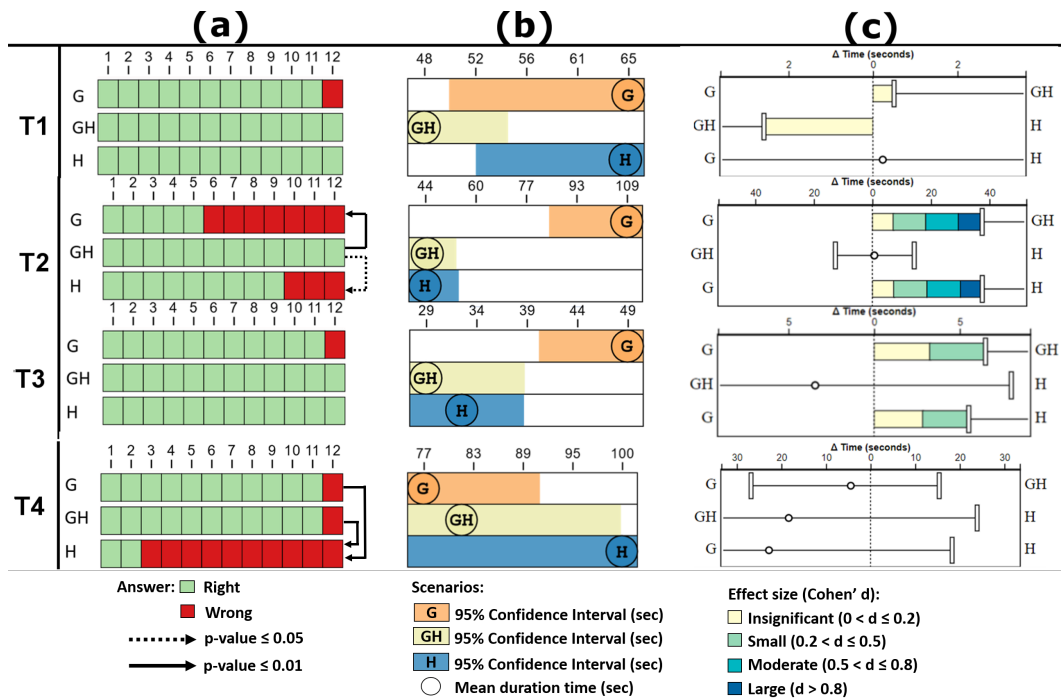

Figure 13. (**a**)—Right/Wrong answers, and pair-wise test using bootstrapping; (**b**)—Response time confidence interval; and (**c**)—Pair-wise test time; for tasks T1, T2, T3, and T4.

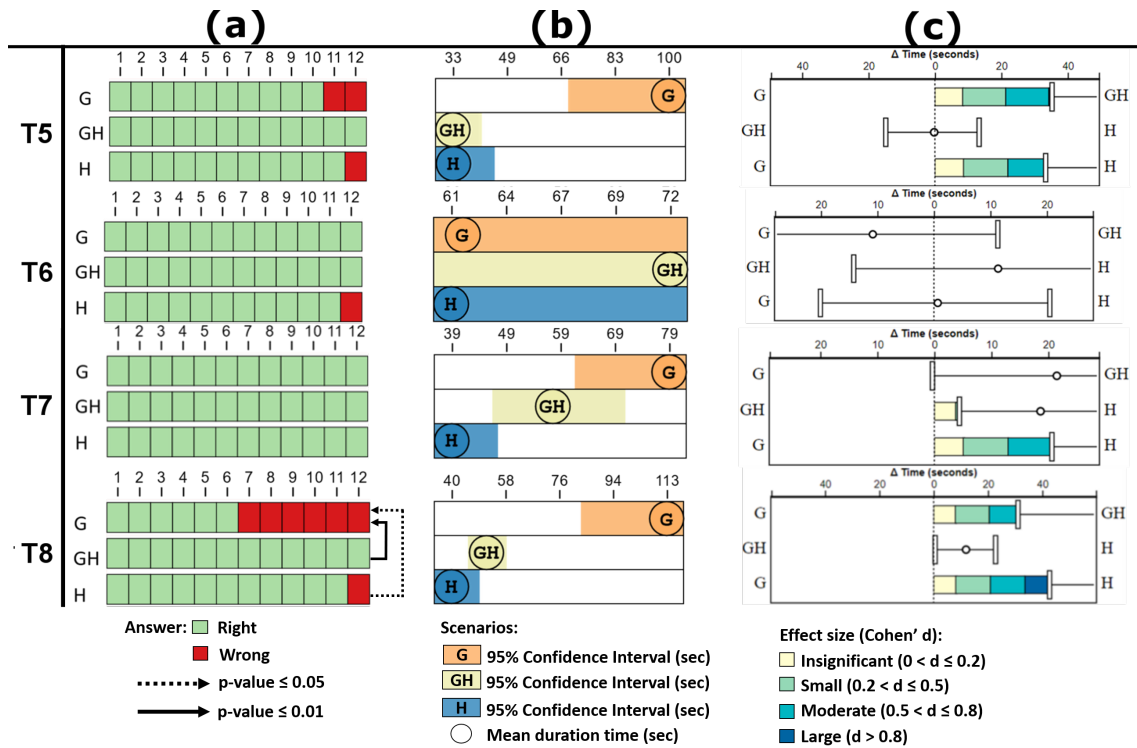**Figure 14.** (**a**)—Right/Wrong answers, and pair-wise test using bootstrapping; (**b**)—Response time confidence interval; and (**c**)—Pair-wise test time; for tasks T5, T6, T7, and T8.

The following topics will guide our analysis of the results: to replace hierarchies by layered glyphs; to locate highest, zero, negative or unique values; to compare groups; and to identify patterns. The analysis of them will support or refute or the hypotheses proposed in Section 5.4.

6.1. Hierarchies versus Layered Glyphs

We considered all user tasks of the study to analyze this criterion. In general, the G, GH, and H scenarios did not show significant statistical differences concerning the result of correct answers by the participants' groups. However, the following tasks stand out: T2 (locate highest values) showed that scenario GH has significantly better accuracy than scenario G (p-value ≤ 0.01) and than scenario H (p-value ≤ 0.05). T4 (locate zero values) showed that scenario GH and G have significantly better accuracy than scenario H (p-value ≤ 0.01 and p-value ≤ 0.01 respectively). T8 (locate patterns) showed that GH and H have significantly better accuracy than G (p-value ≤ 0.01 and p-value ≤ 0.05 respectively). Only task T7 (comparison between groups) had 100% correct answers for all groups.

Considering the values of correct tasks answers and compared to other groups of the same task, the GH scenario stands out with excellent performance, always with the best or sharing the best number of the correct answer.

Figure 15 shows an overview of all task errors by scenario. In general, scenario GH had consistently good accuracies across many task types. On an overview analysis, the use of glyphs without hierarchy (scenario G) seemed to slightly reduce the overall accuracy when compared to the traditional Treemap (scenario H). In other words, replacing all hierarchies with glyphs, in some cases, was not suitable to solve the tasks.

Tasks	Erros			
	G	GH	H	
T1	1	0	0	12
T2	7	0	3	
T3	1	0	0	
T4	1	1	10	
T5	2	0	1	
T6	0	0	1	
T7	0	0	0	
T8	6	0	1	0
Total	18	1	16	

Figure 15. Total of errors in scenarios.

The analysis of the average task execution time for all scenarios point out that the scenario GH presented an excellent execution time average by the participants. We highlight the tasks T6 (locate unique values), T7 (identify patterns), and T8 (compare groups) for analysis. For T6, despite the average time of execution of the GH scenario being higher than H and G, there is no significant statistical difference between GH-H and GH-G. For T7, the average time of GH was higher to the H scenario, presenting a statistical difference between them, but with a small effect size ($0.2 < d \leq 0.5$). For T8, there is no significant statistical difference between H and GH, and their average time are close to each other.

Thus, considering the analysis of correct answers and time average of the tasks, we can refute the hypothesis one (H1). The results point out the GH scenario is the best option, a combination of hierarchies and layered glyphs.

6.2. Search Tasks

The search tasks are the task types that most occurred in the test, for example, to locate the highest values (T2), unique values (T5 and T6), negative values (T3), or zero values (T4). Particularly for these last two items, the traditional Treemap presents restrictions to perform their visual representation and support the search task. Regarding the location of higher values, the GH scenario presented the task T2 with 100% correct answers. Besides, it stands out that scenario GH has significantly better accuracy results than scenario G (p-value ≤ 0.01) and scenario H (p-value ≤ 0.05). The average time between GH and H is similar but statistically different for G with a large effect size ($d \geq 0.8$), which suggests that this scenario may not be suitable for this type of task.

As regards the location of negative values, the analysis of task T3 showed that there are no statistical differences for accuracy between the other scenarios. For this task in scenario H, a label inside the Treemap item represents the negative values. As to the average task resolution time, the GH scenario presented the best average but without statistical difference compared to H, and a statistical difference compared to G, with a small effect size ($0.2 < d \leq 0.5$).

About the location of zero values, task T4 showed that scenarios GH and G outperforms the scenario H (both p-values ≤ 0.01), and there was no statistically significant difference between GH-G. The average time to resolve tasks also did not show statistically significant differences between the scenarios. This task highlighted the Treemap's difficulty in representing zero values and supporting search tasks for them.

Concerning the location of single values, T5 and T6 tasks did not show the statistical difference for accuracy between the scenarios. Still, it is noteworthy that the GH scenario obtained 100% accuracy for both tasks. The average time to resolve tasks also did not show statistically significant differences between the scenarios. However, for task T6, with more attributes for analysis, the GH average time was higher compared to H and G.

Thus, considering the analysis of correct answers and time average of the T2, T3, T4, T5 e T6 tasks, we can confirm the hypotheses H2, H3, H4, and H5, i.e., the combination of hierarchies and layered glyphs is suitable for search tasks.

6.3. Identify and Compare Tasks

Regarding the identification of patterns, all scenarios for the T7 task had 100% accuracy. About the average time between scenarios, the H had a shorter average time. Besides, the following pair-scenarios presented statistical differences, GH-G with insignificant effect size ($0 < d \leq 0.2$), GH-H with small effect size ($0.2 < d \leq 0.5$), and H-G with large effect size ($d > 0.8$).

As regards the identification and comparison of patterns (T8 task), the scenarios GH and H have significantly better accuracy then G with *p*-value < 0.01 and *p*-value < 0.05, respectively. About the average time between scenarios, GH and H are faster than G with moderate ($0.5 < d \leq 0.8$) and large ($d > 0.8$) size effect, respectively.

The profile glyph is used for both T7 and T8 tasks. The scenario G presented the worse average time to T7 and the worse average time and accuracy result to T8. Those results suggest that profile glyph demands more time to identify the target if they are used alone. When the profile glyph is used together with hierarchies, the results are improved and are close to scenario H results. However, it is not possible to confirm hypothesis H6.

7. Final Remarks and Future Works

In this paper, we proposed the addition of layered glyphs in Treemaps to improve the visual representation of multidimensional data capabilities of the technique, as well as to improve the representation of small, negative, and zero values. These representations are quite challenging to be done in the squarified treemap technique.

The proposed glyph is a multilayered square-shaped added to the Treemaps items. Its configuration is dynamic, enabling to change the order of the layers and the used visual variables for each layer. The proposed glyph design use layers to represent categorical and ordinal data and a profile glyph layer for quantitative data. While some layers can represent ordinal data (e.g., text, color brightness), others do not suit this depiction because they do not have any inherent order (e.g., color hue, shape, texture). This opens the space for future research to test new ordinal layers, (e.g., tilt and curvature layers), as well as new categorical layers (e.g., motion) [11]. Since the focus of our study was only to evaluate the efficacy of the layers in search tasks—and the data was synthetic—we considered all variables to be categorical, even if the chosen semantics imply an ordinal relationship. Further studies might evaluate real datasets and consider ordinal data, optimizing the visual mappings to adequate types.

We developed a tool that implemented our proposal, allowing users to visualize more data through the combination of glyphs and hierarchies.

We conducted a task-based user study to compare three different Treemap scenarios: Treemaps with glyphs and hierarchies (GH), Treemaps with hierarchies and without glyphs (H), and Treemaps with glyphs and without hierarchies (G). A total of 36 volunteers performed 8 InfoVis tasks in these scenarios, 12 per each scenario.

The data analysis results showed that replacing all hierarchies per glyphs is only suitable in specific cases, but the use of glyphs combined with hierarchies had consistently good accuracies and response time across different task types. We also highlight the high error rate for the scenario without glyphs in task T4, which required the user finding an item with a zero value. This finding supports the argument that the traditional Treemap has difficulties in representing the zero value.

Adding glyphs to Treemaps items did not increase the response time of tasks by more than a "small" effect size. The approach of adding glyphs to the traditional Treemaps offers considerable potential for representing many dimensions, and also for visualizing small, negative, and zero values.

As future work, we suggest the investigation of the best order, quantity, and relation between visual variables to be adopted in the glyphs of the Treemap layout. Another suggestion is the usage and evaluation of novel designs of glyphs, considering criteria like pre-attention, memorization, and visual quality for limited areas. We also intend to perform new evaluation studies examining other task types and taxonomies. Further studies could use qualitative evaluation methodologies to collect more descriptive information, such as participants' suggestions for glyph design. Besides, there is a potential

of usage expansion for the multilayered glyph in other InfoVis techniques, such as Voronoi, Bubble Tree, Sunburst, among others.

Author Contributions: Conceptualization, A.G.M.S., and B.S.M.; methodology, A.G.M.S., and B.S.M.; software, A.G.M.S., B.S.M., and C.G.R.d.S.; validation, A.G.M.S., B.S.M., R.S.d.A.D.L., and C.G.R.d.S.; data curation, A.G.M.S., B.S.M., R.S.d.A.D.L., and C.G.R.d.S.; investigation, A.G.M.S., B.S.M., and C.G.R.d.S.; writing—original draft preparation, A.G.M.S., and B.S.M.; visualization, A.G.M.S., B.S.M., E.T.C.M., R.S.d.A.D.L. and C.G.R.d.S.; supervision, B.S.M.; project administration A.G.M.S., and B.S.M. All authors have read and agree to the published version of the manuscript.

Conflicts of Interest: The authors declare no conflict of interest.

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