Evaluation of Traditional, Orthogonal, and Radial Tree Diagrams by an Eye Tracking Study

Michael Burch, Julian Heinrich, *Student Member, IEEE*, Natalia Konevtsova, Markus Höferlin, and Daniel Weiskopf, *Member, IEEE Computer Society*

Abstract—Node-link diagrams are an effective and popular visualization approach for depicting hierarchical structures and for showing parent-child relationships. In this paper, we present the results of an eye tracking experiment investigating traditional, orthogonal, and radial node-link tree layouts as a piece of empirical basis for choosing between those layouts. Eye tracking was used to identify visual exploration behaviors of participants that were asked to solve a typical hierarchy exploration task by inspecting a static tree diagram: finding the least common ancestor of a given set of marked leaf nodes. To uncover exploration strategies, we examined fixation points, duration, and saccades of participants' gaze trajectories. For the non-radial diagrams, we additionally investigated the effect of diagram orientation by switching the position of the root node to each of the four main orientations. We also recorded and analyzed correctness of answers as well as completion times in addition to the eye movement data. We found out that traditional and orthogonal tree layouts significantly outperform radial tree layouts for the given task. Furthermore, by applying trajectory analysis techniques we uncovered that participants cross-checked their task solution more often in the radial than in the non-radial layouts.

Index Terms—Hierarchy visualization, node-link layout, eye tracking, user study.

1 Introduction

A common graphical depiction of hierarchical data is by means of node-link diagrams. Nodes are used to represent hierarchical objects and links to express parent-child relationships among those. Node-link tree diagrams are employed in many application domains such as bioinformatics, software engineering, or genealogy to express hierarchical structures. Besides the easy way to draw them, they have many benefits due to the fact that straight links can readily be tracked by the human eye and, hence, lead to an efficient and reliable interpretability of hierarchical structures and substructures. As a drawback, node-link diagrams are space-inefficient representations because of much empty space between the links and, consequently, they suffer from scalability problems for large hierarchical datasets.

To balance the trade-off between structural clearness and space efficiency in node-link tree diagrams, various layouts have been developed. Traditional, orthogonal, radial, and bubble tree layouts aim at making the structure of visualized tree data apparent to the viewer and at using the display space efficiently at the same time. There is already some intuition about how people might inspect such a diagram to interpret the underlying tree structure and to solve certain tasks but specific empirical studies focusing on this topic are rare.

In this paper, we report on an eye tracking study with 38 participants that were asked to identify the least common ancestor of a given set of marked leaf nodes in node-link tree diagrams. We selected this specific task among a set of others because the tree structure has to be understood and some kind of exploration strategy has to be applied to perform the task correctly. By using eye tracking we are able to analyze the strategic behavior of participants and to better uncover the difficulties they have when finding the correct solution in a tree diagram.

As stimuli, we chose traditional and orthogonal tree diagrams where the root node is positioned to each of the four orientations left, right, top, and bottom. By rotating the diagrams we investigated if the tree orientation has any impact on the readability of the tree diagram. Additionally, we chose a radial depiction of the hierarchy as a third major node-link tree layout. This results in nine different types of tree diagrams in total, for which we recorded comparative results for both accuracy and completion times. Figure 1 illustrates the three node-link tree layouts used in the eye tracking study where the root node is oriented toward the top in the non-radial diagrams.

Furthermore, we marked either 3, 6, or 9 leaf nodes in a diagram to explore if an increasing number of marked elements has any impact on the task solving strategy and if completion times are influenced.

Our main hypothesis is that even though radial tree diagrams use the display space more efficiently, they are more difficult to read and to explore. The mapping of the data to a circular shape may lead to misinterpretations and longer exploration times when judging the hierarchical organization of tree elements and separating them into hierarchical substructures due to the fact that subtrees are growing in different orientations.

By tapping the full potential of the eye tracking system, we were able to analyze the exploration behavior of participants solving the given task. The eye tracking data was first visualized and analyzed by heat maps, gaze plots, and areas of interest (AOIs) by the integrated visualization tool of the eye tracking system. In addition, we analyzed saccadic eye movement data by trajectory analysis techniques. We illustrate the usefulness of this automatic analysis technique by computing common subsequences in the participant's gaze trajectories.

The evaluation of the eye tracking data led to many interesting insights. We found out that traditional and orthogonal tree layouts significantly outperform radial tree layouts for the given task with respect to completion times. By exploiting trajectory analysis techniques we uncovered that participants cross-checked the solution in the radial layouts more often than in the non-radial layouts, which may be the reason for the longer completion times for radial layouts.

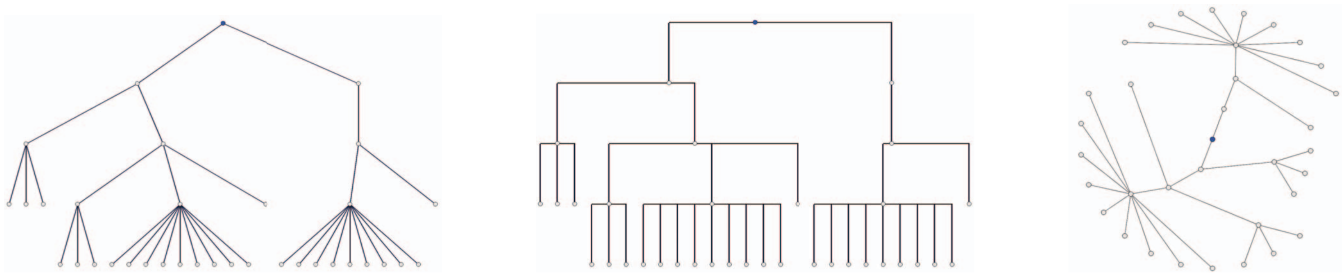
2 Related Work

Research on the effective, intuitive, and aesthetic representation of hierarchical structures is a well-established topic of information visualization. Node-link tree diagrams are a good choice for displaying this kind of data but it remains unclear which type of layout is really useful concerning readability and interpretability on the one hand and space efficiency and scalability on the other hand.

Relations among a set of objects were visualized manually long before the advent of computers. For instance, Euler is one of the pioneers of graph theory, coming up with a solution to the very famous historical problem of the "Seven Bridges of Königsberg" [11] by using node-

- *The authors are with VISUS, University of Stuttgart, Germany, E-mail: {michael.burch, julian.heinrich, natalia.konevtsova, markus.hoeferlin, daniel.weiskopf}@visus.uni-stuttgart.de.*

Manuscript received 31 March 2011; accepted 1 August 2011; posted online 23 October 2011; mailed on 14 October 2011.
For information on obtaining reprints of this article, please send email to: tvcg@computer.org.



(a) (b) (c)

Fig. 1. Three different node-link tree layouts are explored in the eye tracking study. The root node is highlighted by a blue color-coded circle in all displayed diagrams to have similar preconditions for all stimuli: (a) Traditional tree layout. (b) Orthogonal tree layout. (c) Radial tree layout.

link diagrams. The layout of such node-link diagrams is crucial when visually exploring relational data fast and reliably. When laying out a graph in the 2D plane, a list of criteria is available for drawing aesthetic graphs. Minimizing link crossings and preserving symmetries belong to the most important criteria for graph and tree drawing [2, 7]. This results in a reduction of visual clutter that would otherwise lead to a degradation of performance at some task as stated by Rosenholtz et al. [22].

In the domain of hierarchy visualization, node-link layouts are common visual depictions. The work of Eades, for example, focuses on the problem of drawing tree diagrams in an orthogonal layout [10]. The difference to traditional node-link tree diagrams is the usage of ninety degree angled edge bends only and vertically and horizontally arranged lines. Superordinate parent nodes are still visually mapped above their subordinate child nodes, leading to a clear interpretability of the hierarchy.

Bubble or balloon tree diagrams are another way to represent hierarchies by exploiting concepts from naturally growing trees as used by Melançon and Herman [19] or Grivet et al. [12]. The major drawback of these diagrams is the fact that their layout algorithm recursively produces smaller circles onto which each subtree is mapped as shown in the research of Lin and Yen [17]. Bubble tree diagrams are not in the scope of this study since the increasingly smaller nested radial representations are hard to interpret for deep trees.

Radial node-link layouts benefit from space efficiency since the tree grows from a circle center radially to the outside as mathematically demonstrated by McGuffin and Robert [18]. The empty space between links is reduced and, hence, more elements can be represented. Nodes on the same depth in the hierarchy are mapped to the same circular ring around the root node. Radial trees were first published by Eades [10] and Di Battista et al. [7]. The Latour tree visualization system by Herman et al. [13] is an early example of a visualization system that provides several of the above tree diagram types and that enhances them by interactive features.

In literature, it is often speculated that radial tree diagrams are more confusing than traditional or orthogonal diagrams and that these are missing structural clearness even though the display space is used more efficiently. To the best of our knowledge, there is no controlled comparative evaluation investigating the readability and interpretability of different node-link tree layouts by eye tracking.

The question arises if radial node-link tree diagrams have any benefits over traditional or orthogonal diagrams for the same type of hierarchical data apart from using the display space more efficiently or if there are similar weaknesses. There are some comparative studies investigating the usefulness of tree visualization systems but those do not compare the node-link tree representations of this paper.

Wang et al. [24], for instance, evaluated the effectiveness of three types of tree visualization systems. They developed exploration tasks that could not easily be answered by simple algorithmic searches. As a result, they found that visualizations for file hierarchies have different impact on getting deeper and non-trivial knowledge. In earlier work, Kobsa [16] conducted a comparative user study for five well-known tree visualization systems and Windows Explorer.

Today, there is a huge body of work on radial techniques and diagrams, as surveyed by Draper et al. [9], and there is some evidence that many radial visualizations are less useful and less effective than their Cartesian counterparts depending on the data to be visualized. Cleveland and McGill [6], for example, detected in a comparative study that there is a big difference in estimation accuracies for judgments of the same quantitative data in bar charts and pie charts. Stasko et al. [23] reported the results of two empirical studies comparing two visualization tools for depicting hierarchical structures. In contrast to our work, they examined space-filling techniques: a rectangular and a circular representation. Diehl et al. [8] conducted an online user experiment and a controlled experiment to uncover strengths and weaknesses of radial representations. They found out that Cartesian diagrams outperform radial diagrams for the task of redetecting previously marked objects. Our results also confirm that the radial layout cannot keep up with the non-radial counterparts for the task we investigated.

Eye tracking systems are often used to unveil the eye movements of users when solving a given task. Pohl et al. [20], for example, investigated the readability of force-directed, orthogonal, and hierarchical graph layouts with respect to five given tasks. They identified the force-directed diagram type to be superior to the orthogonal and hierarchical graph layouts for three tasks, namely path finding, subgraph, and 4-clique detection with respect to both accuracy and completion times. Burch et al. [4] conducted an eye tracking experiment to compare accuracy and completion times for specific tasks answered by radial TimeRadarTrees [5] and Cartesian Timeline Trees [3] for the visualization of time-series relational data in hierarchical structures. In our work, we focus on analyzing the characteristics of eye movements when participants work with common node-link diagrams.

3 Visualization Techniques

This section reviews the visualization techniques and data models used for our eye tracking study. We use a special hierarchy model to first generate a certain number of random trees with similar statistical properties. These are laid out in a second step by the layout algorithms for each of the three diagram types—traditional, orthogonal, and radial.

3.1 Hierarchy Model

The hierarchy data is generated by a stochastic algorithm. The characteristics of the data are determined by three parameters: the maximal depth $d_{\max}$, the maximal branching factor $b_{\max}$, and the maximal number of nodes $n_{\max}$.

We model the hierarchy in the graph-theoretic sense as a tree

$$H = (V, E)$$

where V denotes the set of vertices and $E \subset V \times V$ denotes the directed edges (parent-child relationships). Edges are always directed from the root to the leaf nodes.

A random hierarchy is generated as follows. Start with one vertex (the root vertex). Then add vertices and edges step-by-step to an existing hierarchy. Process all already existing n vertices $v_1, \ldots, v_n$ and

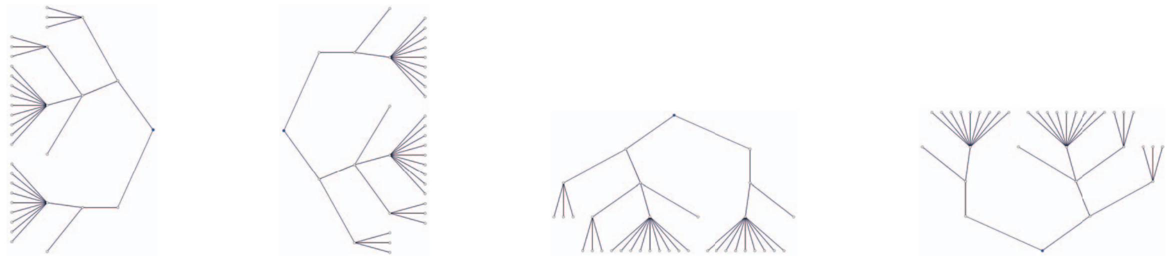


Fig. 2. Traditional node-link tree diagrams may be oriented differently: (a) Root to the right. (b) Root to the left. (c) Root on top. (d) Root at bottom.

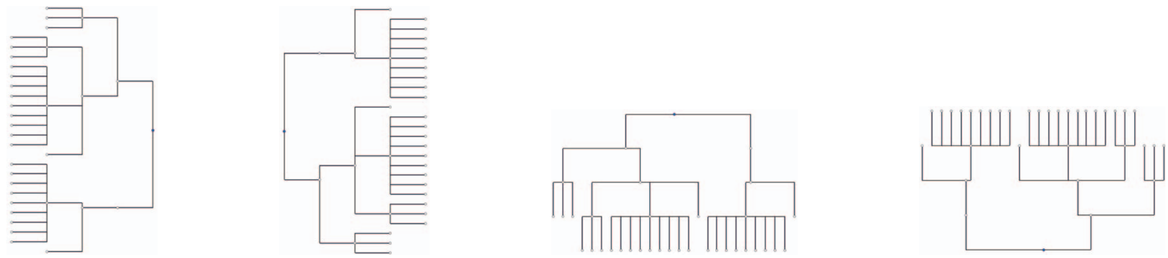


Fig. 3. Orthogonal node-link tree diagrams may be oriented differently: (a) Root to the right. (b) Root to the left. (c) Root on top. (d) Root at bottom.

add a new vertex v_i' to the hierarchy and an edge (v_i, v_i') starting at v_i, $1 \leq i \leq n$ with probability $p(v_i)$, where

$$p : V \longrightarrow [0,1], \;\; v_i \longmapsto \frac{|\{u \in V \mid (v_i, u) \in E\}| + 1}{|\{(v,w) \in E \mid v,w \in V\}| + 1}$$

The new node v_i' and the new edge (v_i, v_i') can only be added if

- the new number of nodes $|V|$ is not greater than the upper bound $n_{\max}$, i.e., $|V| \leq n_{\max}$.
- the new branching factor b is not greater than the upper bound $b_{\max}$, i.e., $b \leq b_{\max}$.
- the new depth d is not greater than the upper bound $d_{\max}$, i.e., $d \leq d_{\max}$.

The position in the hierarchy for the new node v_i' will be randomly chosen in its corresponding subhierarchy.

The algorithm produces an unbalanced and natural looking tree by omitting some branches and by reducing the branching factor in some subtrees randomly. The algorithm generates trees with a power-law distribution of the branching factor within each node and is based on the Barabasi-Albert model [1] for generating random graphs. There are many nodes with a branching factor of zero (leaf nodes) and also many, yet fewer nodes with a branching factor of one. Only very few inner nodes branch with a degree of $b_{\max}$, a property that is also required for scale-free graphs. We chose this hierarchy model to have similar characteristics for all stimuli datasets used in the study.

3.2 Hierarchy Layouts

For our comparative study, we only selected the following node-link tree layouts: traditional, orthogonal, and radial tree diagrams, see Figure 1. We chose them because they are frequently used in many application domains, they are easy to implement, and they follow aesthetic criteria for tree drawing. Furthermore, we use black lines and circles on white background without any additional graphical primitives to keep the diagrams redundant-free and easy to understand and interpret for the participants. In addition, we investigated four orientations for the non-radial representations, see Figures 2 and 3.

3.2.1 Traditional Node-Link Trees

For the traditional tree diagrams, we use a layout that positions the leaf nodes of the tree equidistantly on a horizontal line in a way that each leaf node has a representative spatial horizontal location. This layout is different from the layout according to Reingold and Tilford [21]. We use our layout variant because it can be reused for laying out orthogonal tree diagrams as well, which is important for best comparability between both tree layouts. If the algorithm by Reingold and Tilford were applied to orthogonal layouts, one would face occlusion problems in the orthogonal diagrams.

The x-coordinate of the root node of each subtree is placed in the center of the horizontal space needed to layout the whole subtree. The y-coordinate only depends on the depth of the root node of each subtree. By recursively traversing the tree, we obtain a traditional node-link tree layout, see Figure 1(a). The resulting tree diagram follows important aesthetic rules for graph and tree drawing [7]: nodes with equal depth are located on the same horizontal line and the distance between sibling nodes is fixed. Furthermore, the layout algorithm generates tree diagrams in which isomorphic subtrees are represented in exactly the same way.

3.2.2 Orthogonal Node-Link Trees

Figure 1(b) represents the hierarchical data in the orthogonal layout. Orthogonal tree diagrams are restricted to using ninety degree angles only. To obtain a layout comparable to the traditional diagram, we follow the same strategy as for the traditional case. The root node of each subtree is placed in the center of the horizontal space needed to layout each subtree and the depth of the subtrees' root yields the vertical position. Orthogonal and traditional tree nodes have exactly the same coordinates, given the same dataset. The layouts only differ in the representation of the tree links.

3.2.3 Radial Node-Link Trees

The radial layout places nodes on concentric circles according to their depth in the tree, adopting the algorithm by Eades [10]. We map the leaf nodes equidistantly to the circle circumference. The root node of each subtree is placed in the center of the circle sector on which the leaf nodes of the subtree are located. Figure 1(c) shows an example of the radial layout.

4 Eye Tracking Study

The goal of the eye tracking study is to compare the suitability of three different types of node-link diagrams: traditional, orthogonal, and radial, see Figure 1. We compare accuracy, completion times, and exploration behavior of the participants when they perform a typical task in hierarchy exploration: finding the least common ancestor of a set of marked leaf nodes. The relevant independent variables in the eye tracking study are layout, orientation, and number of marked leaf nodes.

4.1 Hypotheses and Research Questions

We expect that radial diagrams will result in longer completion times than traditional and orthogonal diagrams. Furthermore, we hypothesize that the orientation of the non-radial diagram types will affect the readability of the tree diagram and, hence, completion times. Finally, as a natural hypothesis, we expect that the number of marked leaf nodes will have an effect on completion times: the more leaf nodes are marked, the longer it will take to complete the task of finding the least common ancestor in the tree diagram.

More precisely, we will check the following hypotheses:

- **Hypothesis 1:** The orientation of the non-radial diagram types has an influence on completion times and we expect that the diagram type with the root node located at the rightmost position will outperform the other orientations. We base this hypothesis on the left-to-right reading direction with which our participants (all from Western countries) were most familiar; thus, we expect that trees are most easily read from the leaf nodes if the root node is at the rightmost position.

- **Hypothesis 2:** Traditional and orthogonal tree node-link diagrams outperform radial diagrams with respect to completion times.

- **Hypothesis 3:** An increase in the number of marked leaf nodes leads to higher cognitive efforts in finding the least common ancestor and, hence, in longer completion times for all three diagram types and all orientations.

Hypotheses 1 to 3 can be checked by evaluating the recorded completion times. The following hypotheses can be checked by analyzing the eye tracking data, i.e., the recorded gaze trajectory data:

- **Hypothesis 4:** The non-radial diagrams with the root node oriented to the right are easier and faster to explore than those with the root oriented to any other direction. Consequently, gaze trajectories consist of shorter fixation duration times for the diagrams with the root node to the right.

- **Hypothesis 5:** Traditional and orthogonal diagrams are easier to explore and, hence, distances between subsequent fixation points in gaze trajectories are shorter than in the radial diagrams. Furthermore, fixation duration time is longer for individual fixation points in the radial diagrams and cross-checking is used more frequently in the radial layouts.

- **Hypothesis 6:** The task can be solved faster in diagrams with a smaller number of marked leaf nodes. Gaze trajectory sequences are shorter and sparser with fewer nodes being marked.

4.2 Study Design

We used a repeated-measures study design in a within-subjects style. The variables of interest are:

- **Layout of node-link diagram:** We used three different layouts: traditional, orthogonal, and radial node-link diagrams.

- **Orientation of node-link diagram:** For the non-radial diagrams, we switched the root node position to each of the four orientations: top, bottom, left, and right.

- **Number of marked leaf nodes:** In each diagram, we visually marked three, six, or nine leaf nodes by a red circle.

Each subject performed two trials of each layout type, each orientation, and all three numbers of marked leaf nodes, resulting in 54 trials in total. The participants were shown one diagram of each type (root on top for the non-radial ones) in a block with open-ended questions, which resulted in additional three trials. For this block, each subject was presented three diagrams in sequence for 30 seconds and asked to provide open comments. Each participant was shown the same 57 diagrams in the eye tracking experiment but in a differently permuted order. We randomized and balanced the diagram type blocks and, inside each block, the orientation subblocks were also randomized.

4.3 Stimuli and Task

All datasets were synthetically generated by a stochastic algorithm based on the Barabasi-Albert model (see Section 3.1). The branching factor, the depth, and the number of nodes of each tree dataset were fixed to given bounds. In our experiment, we fixed the maximal branching factor to 20 and the maximal depth to 10. The algorithm was forced to terminate if a tree contains 500 nodes. We randomly color-coded three, six, or nine leaf nodes in red for two tree diagrams of each configuration. To better perceive the marked leaf nodes, we enlarged the radius of the corresponding circles by factor 2 compared to all other non-root nodes.

We investigated the task of finding the least common ancestor of a set of these red-colored leaf nodes in a tree structure. This task was chosen because participants had to apply some kind of task solving strategy to find the correct solution. By this, eye tracking has a real benefit when exploring the recorded eye movement data.

Formally, a tree is modeled in a graph-theoretic sense as a directed graph $H = (V,E)$, where V denotes the set of vertices and $E \subseteq V \times V$ the set of directed edges, see also Section 3.1. The direction of the edges is always from the root to the leaf nodes. A path p between two nodes $v_i \in V$ and $v_j \in V$ is a finite sequence

$$p(v_i, v_j) := v_i \longrightarrow v_{i+1} \longrightarrow \ldots \longrightarrow v_{j-1} \longrightarrow v_j$$

where $(v_k, v_{k+1}) \in E$. We define the least common ancestor $lca(A_1, \ldots, A_n)$ of n nodes $A_1, \ldots, A_n$ as the node C with the largest depth in the tree with the additional property that there are paths from C to A_i, $1 \le i \le n$. Formally, we first define the set of common ancestors as

$$ca : V^n \longrightarrow \mathscr{P}(V),$$

$$ca(A_1, \ldots, A_n) \longmapsto \{C \in V \mid \exists\, p(C, A_1) \wedge \ldots \wedge \exists\, p(C, A_n)\}$$

where $\mathscr{P}(V)$ denotes the power set of V. Then, the least common ancestor is defined as

$$lca : V^n \longrightarrow V,\ lca(A_1, \ldots, A_n) \longmapsto \underset{C \in ca(A_1, \ldots, A_n)}{\operatorname{argmax}}\ depth(C)$$

where the function $depth(C)$ returns the depth of the node C in the tree. The least common ancestor exists and is a unique node, given any number of n nodes $A_1, \ldots, A_n$.

4.4 Pilot Study

Before running the actual experiment, we conducted a pilot study with five participants. The pilot study allowed us to uncover potential design problems in the actual study, to confirm the selection of the task and stimuli, and to estimate the statistical power and the required number of participants and trials. As a result of the pilot study, we decided to reduce the number of stimuli per tree diagram type and orientation from originally nine to six because session times exceeded more than one and a half hours.

4.5 Environment Conditions and Technical Setup

The eye tracking experiment was conducted in a laboratory isolated from outside distractions. The room was artificially illuminated and only a minimum of objects was contained inside. Participants were instructed to switch off their mobile phones to reduce possible distractions during the experiment.

The eye movements were recorded by a Tobii T60 XL eye tracking system with a TFT screen resolution of 1920 × 1200 pixels. Participants sat in front of the display at a distance of about 65 cm, given by the calibration function of the eye tracking system. For the analysis software of the eye tracker, we specified a minimum of 10 pixels covering and a minimum of 30 ms fixation duration as key parameters.

4.6 Participants

We chose a within-subjects study design with 38 participants. All participants reported that they were from a Western country and read texts from left to right. Ten of them were female and 28 were male. Their average age was 24.6 years; the youngest participant was at the age of 19 and the oldest at the age of 54 years. The participants were students of our university, except for 5 participants that recently graduated from our university. 17 of the participants were students of computer science or software engineering; the other participants were mostly students with engineering and science majors. All participants had normal or corrected-to-normal color vision, as confirmed by an Ishihara test and a Snellen chart; 13 of them wore glasses and 5 of them contact lenses. The participants were compensated with EUR 10. The experiments took between 41 to 76 minutes, depending on the speed of the participants.

4.7 Study Procedure

Participants were first asked to fill out a questionnaire about age, field of study, and prior knowledge in visualization techniques. As next step, they read a short manual about the different tree diagrams, followed by test questions to check if they were able to read the diagrams and solve the given task. The test phase was conducted with a different set of stimuli data than the real experiment, serving as a practice run-through.

Then, the actual experiment consisted of four larger parts—the traditional, orthogonal, and radial part, extended by a part with open-ended questions. We permuted and balanced the three layout parts—apart from the open-ended questions that were always presented at the end of the experiment—to compensate for learning and also fatigue effects.

The parts with traditional and orthogonal diagrams were further subdivided into subparts consisting of four blocks each depending on the orientation of the tree. These subparts and their single stimuli were randomized inside each block. After each part, there was a small break of about one minute.

The final block was used to ask open-ended questions about the three layouts. The answers were manually recorded by the operator.

There was a "Give Up" option clearly present throughout the study; however, it was not used by the participants. There was no time limitation for the tasks. The participants were instructed to put emphasis on correctly answering because we were more interested in the tree exploration strategy; we recorded the time it took them to find the correct solution. Putting emphasis on a fast solution would have resulted in higher error rates and in more chaotic gaze trajectories because participants would have been forced to guess an answer regardless of whether it was correct, which was not the intention of this eye tracking study. Once the participants found the solution, they had to confirm it by a mouse click to the correct position on screen. After the experiment part, they had the chance of giving final remarks about which layout and orientation they preferred and which they found easier to explore.

5 Study Results

For the statistical analysis, we included the results of 36 participants because two datasets had to be removed due to technical errors with the experimental setup during the study.

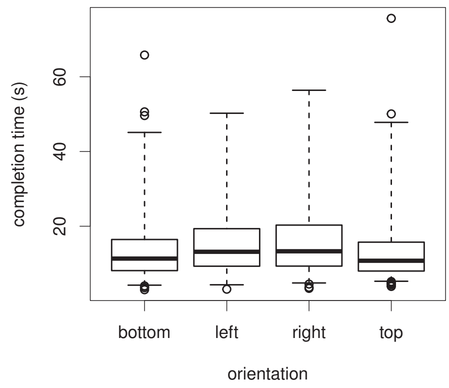


Fig. 4. Boxplots of the distribution of completion times for different orientations. Note that measurements are log-normal distributed. Therefore, adjusted boxplots [15] are used to take into account skewed distributions.

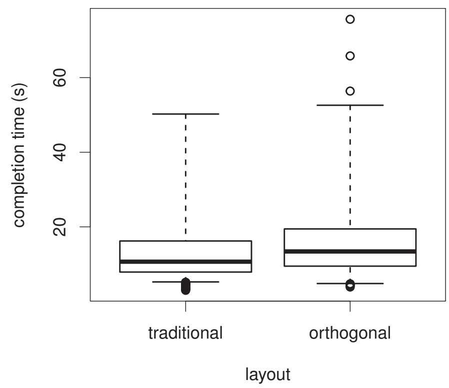


Fig. 5. Adjusted boxplots of the distribution of completion times for traditional and orthogonal layouts. Note that measurements are log-normal distributed.

The overall accuracy of task completion was approximately 97.5%. The low error rate was expected, as the participants were instructed to focus on accurate solutions to the tasks. There was no significant difference between the layout types. Therefore, the following analysis focuses on completion times.

To analyze the effects of the tree layouts and their orientations, the analysis of completion times was split in two independent parts. This was necessary because only one orientation was available for the radial layout. First, the measurements for the radial layout were discarded, and the other layouts were analyzed for an effect of the layout and the orientation. Then, for all three layouts, the orientation with the least average completion time (top) was chosen to compare the effects of the layout.

The measurement data was log-normal distributed such that for all analyses of variance (ANOVA), the log-transformed data was used [14]. As effect-size measurements, we report the partial η^2 as the amount of variation attributable to the respective factor.

5.1 Effect of Tree Orientation

For the analysis of the effect of tree orientation on completion times, time was analyzed using ANOVA with three within-subjects factors

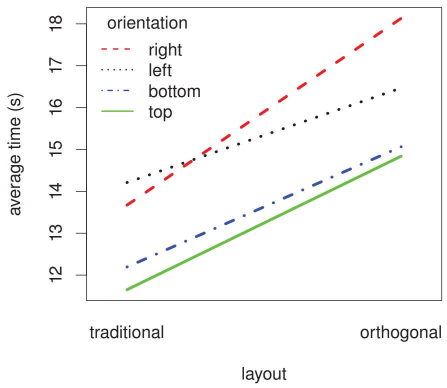


Fig. 6. Interaction plot for tree layout and orientation. Every line represents one orientation, where the endpoints denote the mean completion times for the respective layout (lower means better).

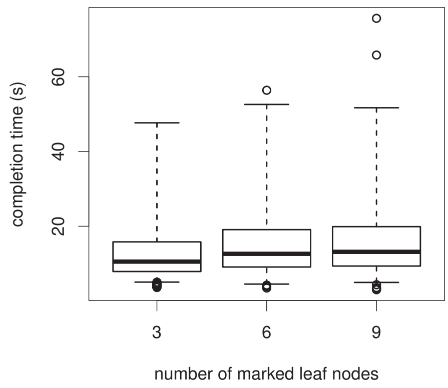


Fig. 8. Adjusted boxplots of the distribution of completion times for different number of marked leaf nodes with respect to traditional and orthogonal tree layouts as well as different orientations. Note that measurements are log-normal distributed.

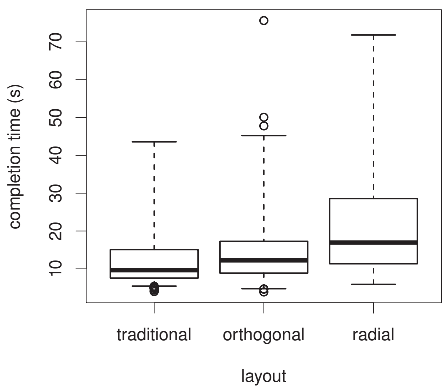


Fig. 7. Adjusted boxplots of the distribution of completion times for traditional (orientation top), orthogonal (orientation top), and radial tree layouts. Note that measurements are log-normal distributed.

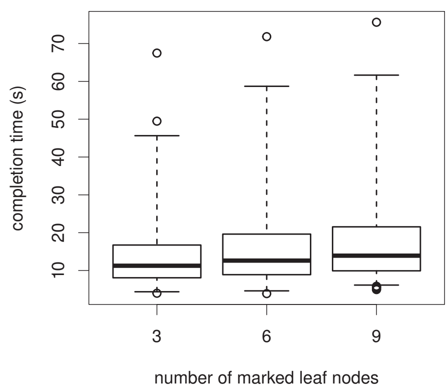


Fig. 9. Boxplots [15] of the distribution of completion times for different number of marked leaf nodes with respect to traditional (orientation top), orthogonal (orientation top), and radial layouts. Note that measurements are log-normal distributed.

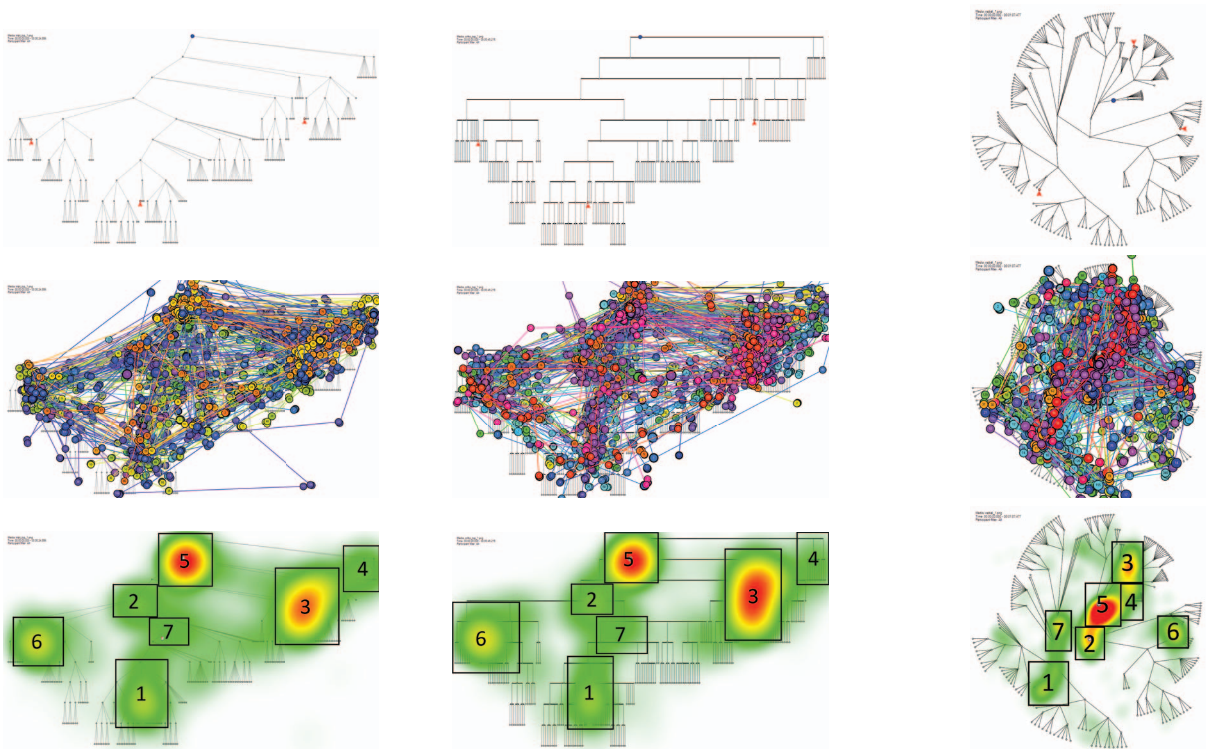
layout, *orientation*, and *number of marked leaf nodes* as well as one between-subjects factor to account for variability between participants. There was a significant effect of the layout on completion time ($F(1,35) = 8.97; p < 0.005; \eta^2 = 0.68$) with mean times $16.13s$ ($SD = 9.59s$) for the orthogonal layout and $12.93s$ ($SD = 6.95s$) for the traditional layout (Figure 5). Also, we found a significant effect of orientation on completion time ($F(3,105) = 4.52; p < 0.005; \eta^2 = 0.53$) with mean times $15.34s$ ($SD = 8.35s$) for left, $15.9s$ ($SD = 9.11s$) for right, $13.63s$ ($SD = 8.12s$) for bottom, and $13.25s$ ($SD = 8.21s$) for top (see also Figure 4). Post-hoc pairwise t-tests showed significant differences ($p < 0.005$, Bonferroni-corrected for multiple comparisons) between left and bottom, left and top, right and bottom, and right and top.

Figure 6 shows the interaction plot of the layout and orientation factors. Both layouts perform fastest if the root is placed on top, followed by placing it at the bottom. While both factors significantly affect completion times, the interaction effect of orientation and layout ($F(3,105) = 4.52; p < 0.005; \eta^2 = 0.14$) mostly originates from left and right orientations (see crossing of lines for right and left in Figure 6). We explain this effect with the preferred reading direction from left to right of the participants, coming from Western countries.

Hypothesis 1, that the root node oriented to the right is the best orientation overall, could not be confirmed by statistically analyzing the completion times for all four orientations. Participants' answers are the slowest when the root is oriented to the right. Only for the traditional diagram layout, there was an interaction effect: the orientation to the right is slightly faster than to the left, but much slower than for top and bottom oriented root nodes.

5.2 Effect of Tree Layout

As the previous analysis showed that both orthogonal and traditional layouts perform best if the root is placed on top (see Figure 6), the following analysis is based on the radial layout compared with the traditional and orthogonal layouts with the root placed on top. For the analysis of the effect of tree layout on completion times, time was analyzed using ANOVA with two within-subjects factors *layout* and *number of marked leaf nodes* plus one between-subjects factor. Again, there was a significant effect of the layout on completion time ($F(2,70) = 5.72; p < 0.005; \eta^2 = 0.71$) with average times $14.84s$ ($SD = 9.63s$) for orthogonal, $11.65s$ ($SD = 6.11s$) for traditional, and 20.95s ($SD = 12.65s$) for radial layouts (see Figure 7). Pairwise t-tests



traditional (destination \ source)	outside	AOI 1	AOI 2	AOI 3	AOI 4	AOI 5	AOI 6	AOI 7
outside	-	59%	35%	59%	22%	35%	36%	47%
AOI 1	17%	-	11%	3%	4%	8%	17%	13%
AOI 2	6%	3%	-	0%	0%	4%	31%	18%
AOI 3	26%	5%	11%	-	40%	24%	0%	11%
AOI 4	6%	1%	0%	10%	-	17%	3%	0%
AOI 5	25%	3%	15%	26%	33%	-	12%	5%
AOI 6	12%	19%	9%	0%	0%	11%	-	5%
AOI 7	7%	10%	20%	1%	0%	1%	2%	-

(a)

orthogonal (destination \ source)	outside	AOI 1	AOI 2	AOI 3	AOI 4	AOI 5	AOI 6	AOI 7
outside	-	55%	38%	41%	45%	42%	66%	43%
AOI 1	17%	-	10%	1%	3%	7%	2%	16%
AOI 2	12%	5%	-	2%	0%	5%	10%	25%
AOI 3	28%	3%	16%	-	36%	32%	5%	6%
AOI 4	4%	0%	2%	11%	-	7%	0%	0%
AOI 5	16%	3%	21%	43%	15%	-	15%	8%
AOI 6	17%	7%	5%	1%	0%	4%	-	2%
AOI 7	5%	27%	10%	1%	0%	3%	2%	-

(b)

radial (destination \ source)	outside	AOI 1	AOI 2	AOI 3	AOI 4	AOI 5	AOI 6	AOI 7
outside	-	56%	17%	12%	8%	16%	33%	40%
AOI 1	21%	-	10%	1%	1%	4%	4%	15%
AOI 2	16%	14%	-	4%	3%	22%	36%	28%
AOI 3	15%	1%	5%	-	23%	31%	4%	0%
AOI 4	1%	0%	2%	43%	-	16%	7%	2%
AOI 5	17%	8%	42%	35%	62%	-	15%	15%
AOI 6	14%	1%	13%	4%	4%	9%	-	0%
AOI 7	16%	20%	10%	0%	0%	2%	0%	-

(c)

Fig. 10. Top row: Hierarchy dataset with three marked leaf nodes (stimuli data). Second row: Gaze plots for the same hierarchy dataset as illustrated in the top row. Third row: Heat maps for area of interest (AOI) determination based on the gaze plot data represented in the second row. Bottom row: Probabilities for direct transition between AOIs. Matrix entries highlighted in the same color belong to the same AOI pair.

showed that differences between radial and other layouts were significant ($p < 0.005$, Bonferroni-corrected for multiple comparisons).

Hypothesis 2 can be confirmed. Non-radial layouts are significantly faster than the radial layout when performing the task of finding the least common ancestor of a set of marked leaf nodes. To understand the reasons for the longer duration when solving the task we have to take into account the eye movement data. There is no significant difference between traditional and orthogonal layouts.

5.3 Effect of Number of Leaf Nodes Marked

Finally, we analyzed the effect of the number of leaf nodes marked in a diagram. First, an ANOVA analogous to the one in Section 5.1 showed that there was a significant effect of the number of marked leaf nodes on completion time ($F(2,70) = 5.72; p < 0.005; \eta^2 = 0.69$) with mean times $12.73s$ ($SD = 6.96s$) for three marks, $14.85s$ ($SD = 8.24s$) for six marks, and $16.01s$ ($SD = 9.82s$) for nine marks (see Figure 8). The ANOVA analogous to Section 5.2 supports these results. Here, the number of marked leaf nodes also had a significant effect ($F(2,70) = 5.72; p < 0.005; \eta^2 = 0.62$) with mean times $13.83s$ ($SD = 8.92s$) for three marks, $15.75s$ ($SD = 10.29s$) for six marks, and $17.86s$ ($SD = 11.89s$) for nine marks (see Figure 9). Post-hoc pairwise testing revealed significant differences only between three and nine marks ($p < 0.005$, Bonferroni-corrected for multiple comparisons). Since both analyses agree on this and an increasing number of marked leaf nodes results in increasing completion times, we confirm Hypothesis 3.

5.4 Analysis of Exploration Behavior

We base our analysis of the participants' exploration behavior on areas of interests (AOIs) that we derived from the density of the heat map representations. The top row of Figure 10 shows the same hierarchy dataset in the traditional, orthogonal, and radial layouts. The second row of Figure 10 represents gaze plots of the participants by the integrated visualization of the eye tracking system for the stimuli based on the datasets from Figure 10 (top row). Each participant is mapped to a different color as given by the integrated eye tracking software and all gaze trajectories are drawn on top of each other. An immense amount of visual clutter is produced and only the hot spots can be derived from this visualization. Therefore, we preprocess the data by first generating heat map representations as shown in Figure 10 (third row) to classify a set of regions that were of special interest for the subjects.

For the analysis, we calculated a transition matrix of the AOIs that contains the relative amount of direct transitions between each AOI to any other AOI, see Figure 10 (bottom). The transition matrix shows the probability to switch from one AOI to another without detours.

The goal of this analysis is to identify major differences in the exploration behavior between the three layout strategies. This analysis method ignores the substantial amount of transitions that begin and end up outside of AOIs (denoted in the first row/column of the transition matrix in Figure 10 (bottom)). To identify detailed characteristics of exploration strategies and to obtain statistically significant and quantitative findings, a more complete analysis approach should be followed, which is left for future work. However, for the comparative and qualitative investigation of the main differences in exploration behavior between the tree layouts, which is the goal of this discussion, our approach is appropriate.

The majority of eye-movement transitions remain inside the AOI that is currently analyzed (traditional: 69 %; orthogonal: 71 %; radial: 64 %). Thus, the participants analyze a particular AOI in detail before moving to another. The transition matrix in Figure 10 (bottom) shows the remainder of the eye movements, i.e., transitions that enter or leave an AOI. Some mentionable AOIs are 1, 3, and 6, since each of them contains a marked leaf node. AOI 5 is also of special interest and includes the root node as well as the solution node (i.e., the least common ancestor of the marked nodes).

The transition matrix leads to the following findings:

- Participants jump more frequently between marked leaf nodes next to each other in the traditional layout than in orthogonal or radial layouts. The transition probability of AOI 1 to AOI 6 (and vice versa) is 19 % (17 %) for the traditional layout, in contrast to 7 % (2 %) for the orthogonal layout and 1 % (4 %) for the radial layout (highlighted in dark blue in the transition matrices of Figure 10 (bottom)).

- Additionally, the distance between the marked leaf nodes strongly affects the transition frequency. For instance, the transitions from AOI 1 to AOI 3 (and vice versa) is much less likely (highlighted in light blue) than the transitions from AOI 1 to AOI 6 (and vice versa) for the non-radial layouts.

- The transition of AOI 2 (which is next to the AOI of the root in all layouts) to AOI 5 (the AOI of the root node) shows an interesting characteristic: while it is more or less common in all layouts to track links back to the root node (highlighted in dark green), the exploration of the radial layout also introduces the transition back from the root node to AOI 2 (highlighted in light green). This might be due to the lack of confidence while exploring the graphs: the participants track the links back again to assure that they tracked them correctly. By this fact, Hypothesis 5 could be confirmed. This also matches with the exploration times, which are nearly twice as high for the radial layout as for the other layouts. Another possibility to explain this fact is that the participants are uncertain where the root node is located, and therefore investigate this area in more detail.

To check Hypotheses 4 and 6, more sophisticated trajectory analyses would have to be applied addressing tree orientations and number of marked leaf nodes. With the data and analysis approach employed, we are not able to confirm or reject Hypotheses 4 and 6.

5.5 Open-Ended Questions

The open-ended questions part of the experiment revealed some interesting insights about the regions in which participants are mostly interested when exploring an unknown tree diagram for the first time. The heat map representations in Figures 11 (a)–(c) show that the participants are mainly interested in the root level and in nodes on lower depths in the trees. Only a few eye fixations rested for a while at the leaf node level.

Additionally, comments given by the participants while inspecting the diagrams were recorded by the operator. Subjects had different findings and impressions depending on the tree layout during the 30 seconds exploration time. For the traditional layout, they had some global findings about the easy interpretability and natural appearance of the diagram. Some participants stated that the orthogonal layout is irritating because of the many parallel links. The radial diagram was said to be not well-arranged and that it was difficult to estimate on which depth a node is located in the tree and also compared to other nodes. Many of the participants also stated that they were able to identify local structures within subareas of the trees for the traditional and orthogonal layouts; they structured the tree into a number of subtrees, found symmetries and asymmetries, and detected subtrees with a high number of leaf nodes. For the radial diagram, they did not report any such local findings.

From these observations, we get the impression that also here the radial layout is considered worst. The traditional tree layout seemed to work best followed by the orthogonal layout where it was reported that the many parallel lines lead to misinterpretations of a tree structure.

The results of the statistical and exploration behavior analysis combined with those of the open-ended questions let us assume that even though radial tree diagrams use the given display space more efficiently than their non-radial counterparts, these lead to interpretability problems because their hierarchical structure is not as clear as in non-radial depictions. Consequently, viewers need much more time to find the correct solution to the given task. As the main reason for this phenomenon, we uncovered some kind of cross-checking behavior that much more frequently occurs in the radial layouts than in the non-radial layouts.

5.6 Qualitative Feedback

The subjective preferences of the participants were further evaluated by analyzing the feedback questionnaires filled out after recording the eye tracking data. We used a Likert scale to evaluate layout preferences (1=very good and 5=very bad) and a check box to find out which orientation the participants liked most.

5.6.1 Layout Preferences

First, we asked the participants to fill out which tree layout they found most motivating, most intuitive, and most suitable to perform the given task. Participants preferred the traditional layout with respect to all three points: motivating (1.42), intuitive (1.42), and suitable (1.76). The orthogonal layout was worse compared to the traditional layout: motivating (2.18), intuitive (2.55), and suitable (2.63). Finally, the radial layout was ranked last: motivating (3.39), intuitive (3.42), and suitable (3.32).

5.6.2 Orientation Preferences

Furthermore, we asked the participants to fill out which orientation of the tree diagram they felt to be most intuitive and helpful when solving the task for the traditional and orthogonal tree layouts. Most of them agreed on having the root node as the topmost element in the traditional diagram (70.3 %). Only 16.2 % liked the root node to be oriented to the bottom, 10.8 % preferred the root node to be placed left and 2.7 % preferred the root node to be placed right.

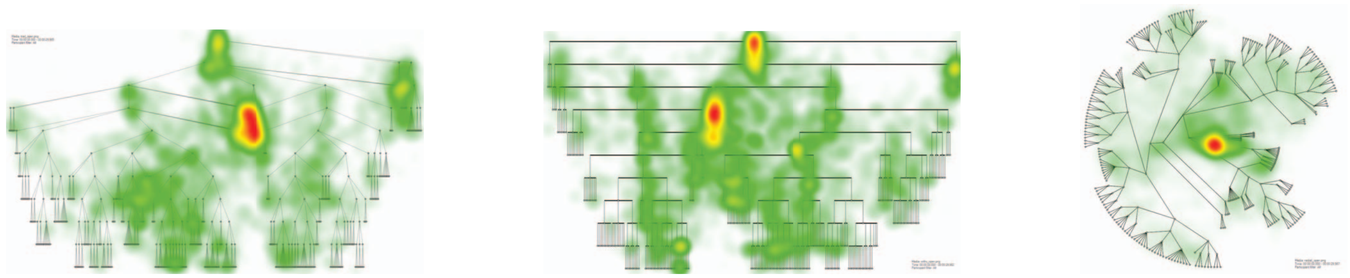
For the orthogonal diagram type, we have similar findings but even more participants liked the root placed at the topmost position (81.1 %). 10.8 % liked it placed at the bottom, 5.4 % left, and 2.7 % right.

The preference for the topmost position for the root node in both traditional and orthogonal diagram types may be explained by the fact that participants had some background in computer science and, hence, were already familiar with this kind of tree diagram orientation.

6 Discussion

Our eye tracking study helped us detect some very interesting results and observations about node-link tree layouts depicting hierarchies. Although radial representations are space-efficient for displaying tree diagrams, these are more difficult to interpret, which can be uncovered by analyzing the gaze trajectories from eye tracking. Task solutions are very often cross-checked in the radial diagrams, which can be a sign for difficulties when interpreting a radial tree. As a consequence, radial diagrams lead to longer completion times when trying to find the least common ancestor of a given list of marked leaf nodes. With respect to our hypotheses, we would argue to choose a non-radial diagram type when representing hierarchical structures by node-link diagrams. Furthermore, we recommend a traditional tree diagram with the root node being oriented to the top.

Our results conform to some degree to former study results addressing the problem of comparing the efficiency of radial representations with their corresponding Cartesian counterparts. Also in this study, the radial depictions of the datasets are significantly outperformed by their traditional and orthogonal counterparts with respect to completion times but with respect to just one single task. We are aware of



(a) (b) (c)

Fig. 11. Heat maps for the open-ended questions for all evaluated layouts in the study: (a) Traditional. (b) Orthogonal. (c) Radial tree diagram.

the fact that the study results might look different if other tasks were evaluated.

7 Conclusion

We reported on an eye tracking experiment with 38 participants comparing three different layouts for node-link tree diagrams: traditional, orthogonal, and radial. Furthermore, we analyzed four orientations for the non-radial diagrams as a second independent variable. We marked a set of leaf nodes and assigned the task of finding the least common ancestor of the marked leaf nodes in the presented tree diagram. All hierarchy datasets were randomly generated by a scale-free model based on the Barabasi-Albert model. We recorded accuracy, completion time, and the eye movements of the participants.

The statistical analysis of the data showed that traditional and orthogonal layouts significantly outperform the radial tree layout with respect to completion times. Additionally, we found out that participants were much faster when the trees are oriented with the root node placed on top. This result is consistent with the preferences the participants reported in the qualitative feedback.

The analysis of the gaze data from eye tracking showed that participants needed more time to analyze radial diagrams because of the time taken to cross-check the potential solution. This phenomenon also appeared in the non-radial diagrams but not that often as in the radial counterparts. For the trees with the root node oriented to the left or the right, participants needed more time because they inspected the subtrees longer in deeper levels, as indicated by analyzing the gaze trajectory data.

In future work, we plan to analyze larger and deeper trees with more leaf nodes marked. By this, we want to strengthen our results about the best node-link visualization for representing hierarchical data. Furthermore, we plan to investigate the performance of different layouts for a more diverse set of tasks. Finally, the analysis of the eye tracking data will have to be extended to include statistically significant results for fine-grained exploration strategies.

Acknowledgments

This work was funded in part by the German Research Foundation (DFG) within the Priority Program “Scalable Visual Analytics” (SPP 1335).

References

[1] A.-L. Barabasi and R. Albert. Emergence of scaling in random networks. *Science*, 286:509–512, 1999.

[2] C. Bennett, J. Ryall, L. Spalteholz, and A. Gooch. The aesthetics of graph visualization. In *Proceedings of Computational Aesthetics in Graphics, Visualization, and Imaging*, pages 57–64, 2007.

[3] M. Burch, F. Beck, and S. Diehl. Timeline Trees: visualizing sequences of transactions in information hierarchies. In *Proceedings of Advanced Visual Interfaces (AVI ’08)*, pages 75–82, 2008.

[4] M. Burch, F. Bott, F. Beck, and S. Diehl. Cartesian vs. radial – a comparative evaluation of two visualization tools. In *Proceedings of 4th International Symposium on Visual Computing (ISVC ’08)*, pages 151–160, 2008.

[5] M. Burch and S. Diehl. TimeRadarTrees: Visualizing dynamic compound digraphs. *Computer Graphics Forum*, 27(3):823–830, 2008.

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

[7] G. di Battista, P. Eades, R. Tamassia, and I. G. Tollis. *Graph Drawing: Algorithms for the Visualization of Graphs*. Prentice Hall, 1998.

[8] S. Diehl, F. Beck, and M. Burch. Uncovering strengths and weaknesses of radial visualizations—an empirical approach. *IEEE Transactions on Visualization and Computer Graphics*, 16(6):935–942, 2010.

[9] G. M. Draper, Y. Livnat, and R. F. Riesenfeld. A survey of radial methods for information visualization. *IEEE Transactions on Visualization and Computer Graphics*, 15(5):759–776, 2009.

[10] P. Eades. Drawing free trees. *Bulletin of the Institute for Combinatorics and its Applications*, 5:10–36, 1992.

[11] L. Euler. Solutio problematis ad geometriam situs pertinentis. *Commentarii Academiae Scientiarum Petropolitanae*, 8:128–140, 1741.

[12] S. Grivet, D. Auber, J. Domenger, and G. Melançon. Bubble tree drawing algorithm. In *Proceedings of International Conference on Computer Vision and Graphics (ICCVG ’04)*, pages 633–641, 2004.

[13] I. Herman, G. Melançon, M. M. de Ruiter, and M. Delest. Latour – a tree visualisation system. In *Proceedings of Symposium on Graph Drawing (GD ’99)*, pages 392–399, 1999.

[14] D. C. Howell. *Statistical Methods for Psychology*. Wadsworth Publishing, third edition, 1994.

[15] M. Hubert and E. Vandervieren. An adjusted boxplot for skewed distributions. *Computational Statistics and Data Analysis*, 52:5186–5201, 2008.

[16] A. Kobsa. User experiments with tree visualization systems. In *Proceedings of IEEE Symposium on Information Visualization (InfoVis ’04)*, pages 9–16, 2004.

[17] C.-C. Lin and H.-C. Yen. On balloon drawings of rooted trees. *Graphics Algorithms and Applications*, 11(2):431–452, 2007.

[18] M. J. McGuffin and J.-M. Robert. Quantifying the space-efficiency of 2D graphical representations of trees. *Information Visualization*, 9(2):115–140, 2010.

[19] G. Melançon and I. Herman. Circular drawings of rooted trees. Technical report, Amsterdam, The Netherlands, 1998.

[20] M. Pohl, M. Schmitt, and S. Diehl. Comparing readability of graph layouts using eyetracking and task-oriented analysis. In *Proceedings of Computational Aesthetics (CAe ’09)*, pages 49–56, 2009.

[21] E. M. Reingold and J. S. Tilford. Tidier drawings of trees. *IEEE Transactions on Software Engineering*, 7(2):223–228, 1981.

[22] R. Rosenholtz, Y. Li, J. Mansfield, and Z. Jin. Feature congestion: A measure of display clutter. In *Proceedings of SIGCHI Conference on Human Factors in Computing Systems (CHI ’05)*, pages 761–770, 2005.

[23] J. T. Stasko, R. Catrambone, M. Guzdial, and K. McDonald. An evaluation of space-filling information visualizations for depicting hierarchical structures. *International Journal of Human Computer Studies*, 53(5):663–694, 2000.

[24] Y. Wang, S. T. Teoh, and K.-L. Ma. Evaluating the effectiveness of tree visualization systems for knowledge discovery. In *Proceedings of Joint Eurographics - IEEE VGTC Symposium on Visualization*, pages 67–74, 2006.