Uncovering Strengths and Weaknesses of Radial Visualizations—an Empirical Approach

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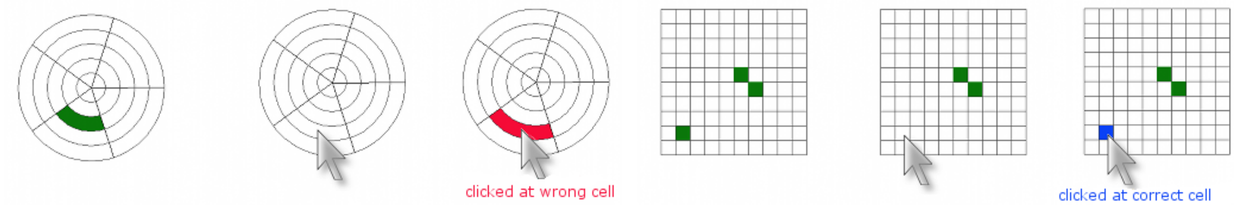

Fig. 1. Memorize and relocate positions in radial and Cartesian coordinate systems.

Abstract—Radial visualizations play an important role in the information visualization community. But the decision to choose a radial coordinate system is rather based on intuition than on scientific foundations. The empirical approach presented in this paper aims at uncovering strengths and weaknesses of radial visualizations by comparing them to equivalent ones in Cartesian coordinate systems. We identified memorizing positions of visual elements as a generic task when working with visualizations. A first study with 674 participants provides a broad data spectrum for exploring differences between the two visualization types. A second, complementing study with fewer participants focuses on further questions raised by the first study. Our findings document that Cartesian visualizations tend to outperform their radial counterparts especially with respect to answer times. Nonetheless, radial visualization seem to be more appropriate for focusing on a particular data dimension.

Index Terms—Radial visualization, user study, visual memory.

1 Introduction

Radial visualizations place visual elements along a circle, ellipse, or spiral on the screen. Many radial techniques can be regarded as projections of a visualization from a Cartesian coordinate system into a polar coordinate system [3]. For example, a pie chart is a radial projection of a bar chart, or a star plot is a radial projection of a parallel coordinates visualization. While there is an increasing number of radial visualization techniques, we know little about why and when they are more appropriate than other techniques. The goal of this paper is to explore when to choose a radial or non-radial approach.

In a recent survey paper [7] on radial methods in information visualization Draper et al. found that "somewhat surprisingly, little effort has been devoted to studying radial visualization as a distinct methodology of its own." From a previous study [3] we learned that it is hard to generalize results from a comparison of particular visualization tools. Moreover, the problem with such a tool comparison often is that the tools do not only differ in the property under study (independent variable). Even if one of the tools is designed to be a reflection of the other, some secondary property (confounding variable) might inevitably differ. For instance, the question arises how to layout labels in radial and non-radial tools without introducing a bias. Hence, in this work we follow a reductionistic strategy by looking at simple and generic visualizations.

Our empirical approach employs the accuracy and speed of visual memorization to compare both kinds of visualizations (Figure 1). Section 2 presents related studies and theories. In Section 3 we introduce the objectives of this work in detail. The first study analyzes these objectives in a wide-ranging user study (Section 4). Moreover, we investigate yet unanswered questions and newly gained hypotheses in a complementing user study (Section 5). We discuss the results with respect to their validity and impact on designing visualizations (Section 6). Finally, Section 7 concludes the paper.

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2 Related Work

Radial representations have their origins in statistical graphics of the 19th century [11]. Florence Nightingale [12] and, earlier, William Playfair became pioneers of radial visualization by using pie charts for statistical graphics [13]. The term radial visualization was introduced much later by Hoffman et al. [9]. Recently, Draper et al. [7] surveyed radial methods in information visualization. They show that to date there already exists a large number of radial representations.

Empirical evaluations comparing radial visualizations to their non-radial counterparts are rare. Actually, for the simple case of pie charts some studies exist. While Cleveland and McGill [5] found pie charts to be less effective than bar charts, because comparing angles is less accurate than comparing lengths, other studies draw partly different conclusions [14]. Some other radial visualizations are also compared with competing tools [10, 1, 15]—often these tools differ in many aspects, not only with respect to the chosen coordinate system type, which impedes the comparison.

In a previous study [3] we also conducted such a tool comparison. We compared two visualization tools for sequences of transactions in information hierarchies: Timeline Trees [2] and its radial counterpart TimeRadarTrees [4]. In contrast to other tool comparisons, both tools were designed to be as equal as possible and only differ in the chosen coordinate system type. In these visualizations, a small Cartesian or radial matrix visualization, called thumbnail, was placed close to each node. We found that these thumbnails were more efficient for the radial version and speculated that users could remember locations better in the radial thumbnails. Furthermore, we found that users could solve tasks faster with the Cartesian tool.

We might also learn something about the difference between Cartesian and radial visualizations from perception research. The judgment of position along a common scale or along identical but non-aligned scales is ranked highest in graphical perception [5]. Even estimating length is done with a much smaller error rate than the estimation of angle and slope, which are very frequent judgments when interpreting radial diagrams.

Moreover, horizontal and vertical directions are the basis for Cartesian diagrams. Changes in those directions are perceived more exactly than any other directions. The human visual system is very sensitive to whether lines or rectangles are in an exact vertical or horizontal arrangement [18]—a fact that may be caused by many vertically and horizontally rectangular shapes that appear in every-day life.

Although intuitive, these general findings are not sufficient to seriously predict the performance of Cartesian and radial visualizations.

3 Objectives

Our work is supposed to contrast radial and non-radial visualizations by conducting a study with reliable and generalizable empirical results. We have to find a way to implement this goal in an experimental setup. To this end, we propose a generic visualization and task, and derive a testable hypothesis from previous studies.

But first of all, we clarify the central concepts of this work. The term *radial visualization* denotes visualizations that are based on a dominating radial structure like a ring, an ellipse, or a spiral, in other words, visualizations in a polar coordinate system. As the counterpart of radial visualizations, we define *Cartesian visualizations* as based on a dominating rectangular structure, in other words, visualizations in a Cartesian coordinate system.

3.1 A Generic Visualization and Task

We chose to visualize an $n \times n$ matrix in a common rectangular shape as the Cartesian visualization. Its radial counterpart in a polar coordinate system is a circle split into n sectors and n rings. Colored cells represent the information encoded by the visualization (Figure 1).

Such a visualization is a kind of prototype for visualizations based on a Cartesian or radial grid pattern. A grid is the basic structure in many visualizations like matrix and table visualizations, icicle plots of hierarchies (radial and non-radial), or scatter plots (in Cartesian and polar coordinate systems). Nevertheless, there exist many visual concepts not covered by such a grid visualization. For example, some visualizations mainly build on lines and curves, others rely on colors and shapes or work with textures. In conclusion, the proposed visualization is a generic version of an important visualization type, but not representative for all visualization types. Hence, the results and observations of the presented studies will primarily apply to visualization based on a grid layout.

Additional to the generic visualization, we need a generic task the users should solve with the help of this visualization. Based on our experience with different information visualization tools, we found that memorizing positions of visual objects for a few seconds is a key task in many different usage scenarios like

- comparing non-neighboring objects (e.g., judging the heights of two bars in a chart);
- locating changes in an animated visualization (i.e., comparing the current visualization to your abstract mental map of the visualization);
- going back and forth between two views (e.g., switching between detail view and context view);
- resuming to work with a visualization (e.g., after looking at the keyboard or switching between windows);
- jumping back and carrying on while systematically searching a diagram (e.g., thoroughly scanning for outliers).

In general, each of these tasks includes moving the eyes over longer distances in the visualization while memorizing positions for a few seconds. It is associated with the users' spatial memory, or more precisely, their object location memory. But the details of the cognitive processes behind object location memory are still controversially discussed [17].

Similar object location tasks were already used to evaluate visualization paradigms like 2D versus 3D [6, 16] or orientation and layout of visual structures [19]. While these studies work with a somewhat more complex tasks—memorizing sequences of positions or larger sets of objects—we preferred memorizing a small set of positions only for a few seconds to partially simulate the process of reading a visualization.

It is an unanswered question how far this abstract task of memorizing positions influences complex tasks in real-world applications. But this would also be the case for other abstract tasks. In contrast, a task taken from a concrete application would be less generalizable. We picked this particular abstract task because it is relevant for a broad spectrum of concrete applications as the above list and the included examples show. Nevertheless, more research on identifying generic tasks for evaluating information visualizations needs to be done to further justify such a choice.

3.2 Hypothesis

In a previous eye-tracking study [3], we compared the Timeline Trees [2] and the TimeRadarTrees [4] visualization tools, the latter being the radial counterpart of the first. The participants had to solve different tasks related to sequences of transactions. It turned out that the Cartesian tool outperformed the radial one for most, but not all tasks. For those tasks where the radial tool did better, we speculated that it might be easier to distinguish and remember locations in a radial coordinate system. But as discussed in Section 2, there are other results that suggest that Cartesian visualizations might perform better. When designing the current study, there were different expectations among the current authors about the outcome, but we all agreed that both approaches would perform differently. Hence, we had to formulate our expectations as an undirected hypothesis.

Hypothesis 1. *There exists a clear difference in the accuracy and speed of perceiving object positions in Cartesian and radial coordinate systems.*

4 Study I

The first study was intended to test the formulated general hypothesis and, furthermore, to provide a basis for an exploratory analysis for further findings. In particular, we wanted to analyze spatial phenomena like cells and regions with an exceptional task difficulty. To this end, we needed a broad participation of users producing a reliable data set. Hence, we decided to design a short web-based experiment to ensure easy access.

4.1 Method

The experiment was implemented as a sequence of web pages including an interactive Java applet. The experiment addressed German speaking Internet users, who we recruited via e-mail newsletters, website announcements, and forum contributions. At the beginning of the experiment, the participants were asked to provide some personal information including age, gender, native language, education, computer experience, and visual problems. Additionally, some technical aspects like screen resolution, browser, and operating system were recorded.

1229 participants initially started the experiment. To improve the data quality, we excluded the data sets of those participants who did not finish the study, who did not answer any question in time, or who did not provide any personal information. We ended up with 674 remaining participants (384 male, 268 female, 22 gender unspecified). Since the personal data was provided voluntarily, we have only partial information about our participants. Nevertheless, the data shows that they had quite a mix of different backgrounds: 39 were still at middle or high school, while 142 had already an academic degree; among the remaining participants we had 222 students including 37 from computer science, 35 from psychology, and 32 from social sciences. In addition to the personal data, we logged some information about the computers used by the participants. While a commercial operating system was clearly dominating (92% Windows, 4% Linux, 4% Mac OS), the open source browser Firefox was mostly used to access the web page of the experiment (60% Firefox, 28% Internet Explorer).

The online experiment took about three minutes (including the questionnaire). The experiment is split into eight parts, each part consisted of two images as sketched in Figure 1. The first image was shown for one second. The task of the participants was to memorize the positions of the green colored cells in the first image. Then the screen was cleared for another second and the second image was shown at a different position on screen. The second image only differed from the first image in only one cell. This cell was colored in the first image but not in the second one. The participants had to click at the position of this cell. We restricted the time to answer to at most four seconds to motivate the participants to work efficiently.

We considered the coordinate system type—Cartesian or radial—as an independent variable of the experiment. Additionally, we toggled the number of highlighted cells between either one or three. We wanted to know whether this variation of the memorization task influences the difference between Cartesian and radial visualizations. The two independent variables were set randomly for each of the eight parts.

We also varied the size of the visualization to prevent ceiling or floor effects caused by too high or too low task difficulties. Since we included different sizes only to get different difficulties, there was no need to vary size independently. In particular, the experiment started with a resolution of 4×4 cells. This resolution was incremented in three steps: 8×8, 12×12, and 16×16. Since the experiment consisted of eight parts, this procedure was repeated once.

For each part, we recorded as dependent variables the correctness of the answer as well as the time the participant needed to answer.

4.2 Results

In the following we discuss the results with respect to the two aspects of Hypothesis 1 separately. First we look at the accuracy of perceiving object positions, then we turn to the perception speed. Subsequently, we explore spatial effects in the visualization like cells or regions that are easier to memorize than others.

We use descriptive statistical methods to reflect observations in numbers and diagrams. If the particular observation is covered by a proposed hypothesis, we also conduct inferential statistics and assume observations where $p < 0.05$ to be statistically significant results. For proper use of statistical testing, all hypotheses have to be determined in advance. The nature of the other observations is more explorative. They have to be considered preliminary and need further evaluation, post-hoc significance tests of these observations would be questionable. Nevertheless, the broad participation increases their credibility.

In the following, we call those findings related to planned hypotheses *results*, and those based on post-hoc analysis *observations*.

4.2.1 Perception Accuracy

Figure 2 summarizes the main results of the first study in form of mean values. It contrasts the average percentage of correct answers of Cartesian and radial visualizations under different experimental conditions. In general, we consider an answer as correct if the participant hit the right cell—we do not further differentiate the false answers.

The average percentage of correct answers for a participant is 60% for Cartesian visualizations while it is only 55% for radial visualizations. A Wilcoxon test—a non-parametric statistic test for repeated samples[1]—confirms this difference to be highly significant ($p = 0.001$). Hence, we are able to formulate a first result:

Result 1. *With respect of answer correctness, users perform significantly better in the Cartesian visualizations than in the radial ones.*

[1]We chose this test, which makes no assumptions on the distribution of the variable, because it is the more conservative way.

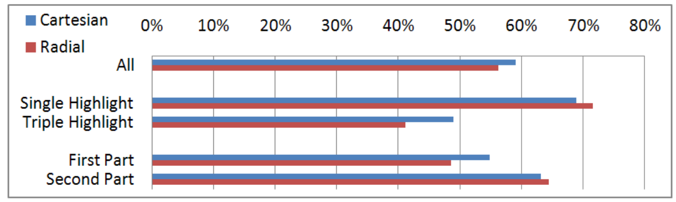

Fig. 2. Study I: Average percentage of correct answers split by experiment condition.

First of all, this result confirms that there is a significant difference in the perception accuracy of positions in Cartesian and radial visualizations. Moreover, the result is in favor of Cartesian visualizations. But in the following we want to take a closer look at the reasons for this outcome.

In the next step of our analysis, we also consider the number of highlighted cells, the second independent variable. This two-stage variable differentiates the answers into visualizations with a single highlight and those with triple highlights (Figure 2). Obviously, the task of memorizing three highlighted cells is more difficult than just memorizing one.

Observation 1. *Memorizing positions of single cells is easier than memorizing positions of three cells.*

But the answer correctness only drops from 70% to 45%, not antiproportional to a third of the initial correctness value, as one could have expected. Reasons might be that the participants were able to actually memorize more than one position or that they memorized relative positions or patterns of the highlighted cells instead of the exact position in the coordinate system.

When we look at the difference between Cartesian and radial visualizations, we observe that radial visualizations only yield inferior correctness values for triple highlights. For a single highlight they even outperform the Cartesian ones.

Observation 2. *Memorizing single cells is easier in radial coordinate systems while memorizing three cells is easier in Cartesian coordinate systems.*

This observation refines the statement of the first result to some extent. It shows that, under certain conditions, also radial visualizations could be more appropriate. Furthermore, the observation raises the question why the participants achieved better results in the radial version for single highlights. Perhaps the additional visual context provided by the center point of the radial version helps more when just one cell was highlighted. The second study (Section 5) will explore this important issue in greater detail.

Not only the different conditions, but also temporal trends might provide interesting insights. Since we repeated the sequence of differently sized visualizations twice for each participant, we are able to split the experiment into two equally difficult parts. Figure 2 not only shows that there exists a clear performance enhancement—a learning effect—between the first and the second part, but also documents a changing relation between the Cartesian and radial visualizations: While the Cartesian version provides considerably better results in the first part, the radial version performs slightly better in the second part.

Observation 3. *In the first four visualizations (first part), users gave the correct answer more frequently for Cartesian visualizations (first part), but radial visualizations performed slightly better for the second four visualizations (second part).*

This shifting learning effect suggests that radial visualizations are a bit harder to learn, but are not harder to read for trained users in principle. But the short duration of the first experiment does not allow drawing such extensive conclusions for sure. The second study will analyze these temporal factors more precisely.

4.2.2 Perception Speed

The perception accuracy is of course most important for a visualization, but also the perception speed influences its readability. For instance, a visualization where we need twice as long for a particular task is less valuable. For our experiment we record the perception speed in terms of answer times. Since we do not know why the participants did not answer correctly—they might just clicked anywhere or wanted to answer too fast—we only take answer times of correct answers into account. Figure 3 shows the average answer times for those correct answers, again split by different experimental conditions.

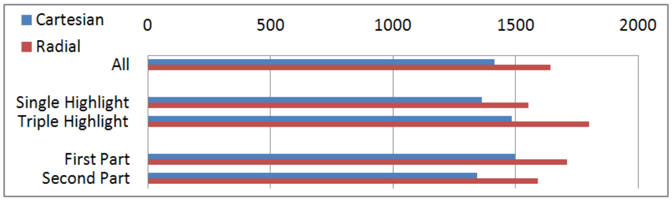

Fig. 3. Study I: Average answer times in milliseconds only considering correct answers and split by experiment condition.

The chart illustrates that the participants answered considerably faster for Cartesian visualizations. The average answer time amounts to 1417 ms for the Cartesian condition and 1661 ms for the radial condition. This difference of about 200 ms does not only hold for the sum of all answers, but also to a similar extent for each particular condition. Consequently, the Wilcoxon test rates this effect to be highly significant ($p = 0.000$).

Result 2. *Users need significantly shorter time to answer correctly in the Cartesian visualizations than in the radial visualizations.*

Together with Result 1, this result confirms Hypothesis 1: *There exists a clear difference in the accuracy and speed of perceiving object positions in Cartesian and radial coordinate systems.* Moreover, Observation 2 and Observation 3 provide first hints at the reasons for the difference.

4.2.3 Spatial Effects

We do not expect the task of memorizing a particular cell to be equally difficult for each cell. Borders might provide a visual anchor, cells become smaller towards the circle center, or certain orientations might be easier to recognize. These spatial effects may influence the individual, cell-specific difficulty of the task. When designing a new visualization, information on such effects might help to avoid problems.

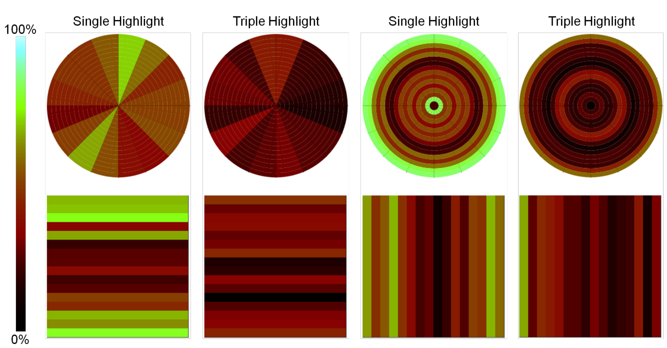

Fig. 4. Study I: Average percentage of correct answers summarized for Cartesian visualizations by row and column, and for radial visualizations by sector and ring.

To this end, Figure 4 depicts the percentage of correct answers in form of heatmaps. They show the cell-specific answer correctness of the 16 by 16 cell visualizations. To provide a better overview, we summarized the Cartesian ones by row and column, and the radial ones by sector and ring. On the linear optimal color scale, bright colors indicate high hit rates while dark colors represent more difficult regions.

In the Cartesian visualization, remembering a cell adjoining a border line is certainly easier than remembering the exact position of a cell somewhere in the middle of the blank Cartesian matrix. Figure 4 supports this assumption. We observe high hit rates for the first row, the last row, the first column as well as the last column. The neighboring rows and columns also show high rates, but not as consistent as the outermost ones. The effect is very similar in the radial visualizations. Here, the outermost ring also performs best.

To validate these observations, we compare border cells to non-border cells as well as we compare outer cells to inner cells (Figure 5). We define border cells as cells that directly adjoin the outer border of one of the graphics. The term *outer cell* denotes cells, for Cartesian visualizations, that are nearer to the border than to the center on either the horizontal or the vertical axis and, for radial visualizations, that are element of a ring nearer to the border than to the center.

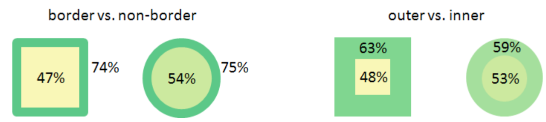

Fig. 5. Study I: Average percentage of correct answers split by border and non-border cells as well as by outer and inner cells.

We observe clearly higher answer correctness values for border and outer cells than for non-border and inner cells. The difference is, however, larger for Cartesian visualizations, which might relate to the additional visual context provided by the circle center.

Observation 4. *Outer cells and especially border cells are easier to memorize than inner cells and non-border cells, respectively.*

In the radial visualizations, cells get smaller and smaller from the circle circumference to the circle center. An intuitive assumption is that the smaller the cell, the harder it is to memorize. But contrarily, in Figure 4 we see a dark sequence of rings—indicating low hit rates—about half way between center and circumference while rings towards the center get brighter. Only the very small cells in the direct sphere of the center perform comparably bad again.

Observation 5. *In radial visualizations, positions on rings about half way between center and circumference seem to be most difficult to memorize.*

This observation adds to our assumption that the center of the circle plays a crucial role in radial visualizations. It alleviates the difficulties of memorizing the cells near the center, although they are smaller. Notably, the difference is much less for three highlighted cells than for one. The remaining two points might adopt the role of the center point in providing a visual context.

The heatmaps of the Cartesian visualizations (Figure 4) hint at another interesting effect. Comparing the rows at the top to the rows at the bottom, we observe slightly higher answer correctness values at the top. Similarly, the columns on the left hand side record higher hit rates than the ones on the right hand side.

Figure 6 investigates this phenomenon in detail. It differentiates the percentage of correct answers by quadrants, for the Cartesian and the radial visualizations, respectively.

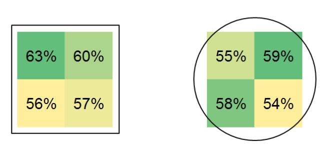

Fig. 6. Study I: Percentage of correct answers split by quadrant.

We clearly observe an decreasing correctness from left to right as well as from top to bottom. This direction is equivalent of the dominant reading direction of the participants—experiment instructions were given in German. Such a reading direction effect is well-known in perception research. For example, Eviatar [8] shows in a cross-cultural study on attention that English readers respond faster to a stimulus on the right hand side than to one on the left hand side. Since they observed the opposite pattern for Hebrew readers, we assume the effect as observed in our experiment also to depend on the culturally dominating reading direction of the user.

Observation 6. *There exists an effect of reading direction for Cartesian coordinate systems. Perception accuracy increases from left to right and from top to bottom.*

Surprisingly, the radial visualizations does not show a similar reading direction effect (Figure 6). We find high hit rates along the secondary diagonal and low ones along the primary diagonal instead. The dominating center point of the radial visualization might be an explanation of the lacking reading direction effect but cannot illuminate this particular outcome.

In a Cartesian visualization the horizontal axis might represent one dimension, the vertical axis might add another. Analogously, sectors and rings are able to represent two dimensions in radial visualizations. In both cases we expect to be free to switch both dimensions.

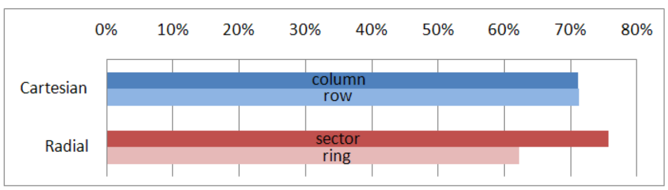

Fig. 7. Study I: Percentage of correct answers with respect to rows and columns or sectors and rings.

To find out whether the perception accuracy is equal on both axes, we rate each answer on two scales: Whether the answer hits the correct row/sector and whether it hits the correct column/ring (Figure 7). In Cartesian visualizations there does not exist any difference between both types of accuracy, but for radial visualization the results show a clear preference for sectors. While the participants hit the correct sector in 76% of the cases, they only hit the correct ring in 62%. Hence, this observation suggests to put the more important or the more detailed dimension on the sector axis.

Observation 7. *When depicting as many sectors as rings in a radial visualization, sector positions are easier to memorize than ring positions.*

4.3 Unanswered Questions

The aim of the first study was to recruit a large set of participants for a simple and brief experiment and thus gain a reliable data set to investigate the differences between Cartesian and radial visualizations. But the simplicity as well as the briefness of the study leave some questions unanswered.

The first aspect is the simplicity of the visualization. Many real-world visualizations, on the contrary, are very complex—especially those that target visual analytics applications. Nevertheless, they still require their users to exactly memorize positions of visual objects. But the dense visual elements might form patterns and shapes that support orientation on the diagram. For each object they might provide a recognizable visual context.

We already touched the subject of visual context when discussing the role of the circle center in radial visualizations. The existence of this landmark might be the reason for the good performance of radial visualization when only one cell was highlighted. It may as well abet the high hit rates in close distance to the circle center and impede a reading direction effect in radial visualizations. But since such a center is inextricably linked to a radial representation, we cannot judge the role of providing a visual context independently.

A new hypothesis for the second experiment therefore addresses providing an additional visual context like the one available in more complex and dense visualizations. Based on the results and observations of the first study, we formulate this hypothesis as follows. We assume a weaker effect for radial visualizations because a context implicitly is provided by the circle center.

Hypothesis 2. *Adding a visual context to Cartesian as well as radial coordinate systems will increase the perception accuracy. This effect is supposed to be stronger for Cartesian visualizations.*

The second aspect is the briefness of the experiment. As brought up in Section 4.2.1, a different learning effect of both visualization types might have biased our results. While in the first half of the experiment the Cartesian visualizations did well, the radial visualization broke even or actually slightly performed better than their Cartesian counterparts in the second half. This observation implies that there might be a more intense learning effect for radial visualizations, and it questions the overall better performance of the Cartesian visualizations.

In conclusion, our next goal is to analyze this learning effect in detail. This obviously requires a longer experiment. We express our assumptions in the following hypothesis.

Hypothesis 3. *Perception accuracy will increase at the beginning of the experiment for Cartesian as well as radial coordinate systems. We assume this effect to be more pronounced for radial visualizations.*

5 Study II

The second study complements the first study by testing the two newly proposed hypotheses in a longer experiment based on a more complex setup. The longer duration and the already very broad data set of the first study relax the need for many participants.

5.1 Method

We reused and extended the implementation of the experiment environment of the first study. Instead of publishing the experiment online, we spread the instructions and the experiment application by e-mail. Since we could not expect to recruit as many participants for such a more intense and more time-consuming experiment, we just targeted people from our working environment.

21 persons (18 male, 3 female) participated voluntarily—all with academic background: 8 computer science students, 12 computer science PhD students and 1 psychology graduate. In contrast to the first study, this group is more homogeneous, and they can be considered as users with more expertise concerning visualizations.

We complement the two independent variables—coordinate system type and number of highlighted cells—by a third variable: Hypothesis 2 requires to add some visual context to the visualization and to vary this context independently.

We thoroughly considered different strategies to provide such a context. To actually make a difference, the additional visual elements had to form a kind of recognizable pattern. Such patterns usually originate from the internal characteristics of the data, which we had to simulate. Instead of using specific patterns like bars or clustered objects, which might have biased the results, we decided, as a neutral solution, to randomly mark additional cells of the visualization. In particular, we colored up to 20% of the cells in a gray background color (Figure 8). Although randomly selected, the cells form recognizable local structures.

In the second study we refrain from varying the size of the visualizations. Based on our experience from the first study, we were able to define an appropriate task difficulty in advance. We set the size of the visualizations to 20×20 cells. We chose the larger size to balance the assumed positive effects of the provided visual context.

The single tasks still proceeded like in the first study—a visualization with marked cells is shown to the participant, the image disappears and reappears in a different position, the participant has to find

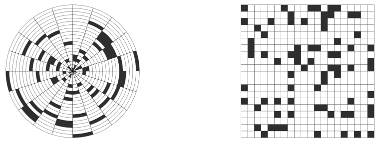

Fig. 8. Random background patterns in a radial and a Cartesian visualization as used in the second study.

and click the missing marked cell. Once again, we measured answer correctness and answer time (restricted to correct answers) as dependent variables.

The three two-stage independent variables (coordinate system type, number of highlighted cells, and background) result in eight possible combinations of specific tasks (Figure 9). We presented these eight task in a random order to the participants and repeated this procedure 20 times. Thus, each participant had to click a memorized position 160 times in total, which took about 15 minutes.

5.2 Results

We discuss the results of the second study with respect to Hypothesis 2 and Hypothesis 3 successively. First, we focus on the impact of providing a visual context, and second, we analyze how the participants' answers change over time.

5.2.1 Visual Context

Visual context is provided by adding background patterns, but also, more implicitly by highlighting three cells instead of one. We varied these two variables independently which leads to four combinations. Figure 9 shows the answer correctness for these combinations, each subdivided into Cartesian and radial visualizations.

	Single Highlight	Triple Highlight	
No Background	41%	35%	Cartesian
	50%	32%	Radial
Background	86%	49%	Cartesian
	77%	38%	Radial

Fig. 9. Study II: Average percentage of correct answers split by experiment conditions.

To test our hypothesis, we used an analysis of variance (ANOVA). A three-way ANOVA with repeated measure analyzes the effect of the three independent variables—the coordinate system type, the number of highlights, the availability of background patterns—as well as interaction effects between these variables.

We start with comparing the percentage of correct answers between the new background condition and the old version without background. First of all, the overall difficulty of memorizing positions decreases when providing such a visual context: Without background patterns 40% of the participants answered correctly compared to 63% with background patterns. The ANOVA rates this main effect as statistically significant ($F_{1,20} = 107.315$, $p < 0.001$).

Result 3. *Adding visual context in form of background patterns increases the performance of the participants significantly.*

This is, of course, a result worth mentioning, but not a result we seriously doubted. It is more interesting to look closer at the behavior of Cartesian and radial visualizations in comparison. Here, we find a larger improvements for the Cartesian versions. While both perform about equally well without background, Cartesian visualizations clearly exceed radial visualizations when background is available. This shifting difference is equivalent to the interaction effect between the coordinate system type and the availability of background patterns, which the ANOVA confirms to be significant ($F_{1,20} = 8.190$, $p = 0.010$).

Result 4. *Providing visual context increases the performance more in Cartesian coordinate systems than in radial ones.*

An explanation of this result might be that in radial visualization there is already some visual context provided by the circle center. Hence, adding more context is less efficient than in Cartesian visualizations where no context was available. To substantiate this explanation, we look at the effect of the number of highlighted cells. As we have already seen in the first experiment, memorizing three cells is harder than memorizing just one (Observation 1), but the additional context provided by three cells might moderate the effect. This moderation is reflected as an interaction effect between coordinate system type and the number of highlights by the conducted ANOVA. It is rated significant ($F_{1,20} = 6.585$, $p = 0.018$), which confirms the initial observation. Again, the already available context in radial visualizations provided by the circle center might explain this effect. Another theory might be that it is easier to remember patterns in the Cartesian visualization than in the radial one.

To explore the result in greater detail, Figure 10 depicts the answer correctness as heatmaps in a Cartesian and radial version for the experimental conditions. To filter the noise caused by the random distribution of the clicks (3360 clicks are distributed over 400 cells and eight conditions), we smoothed the diagram by summarizing each cell with all neighboring cells. In particular, we compute the average correctness of the cells weighted by the number of clicks. Since we allowed these areas to overlap, we did not reduce the number of cells.

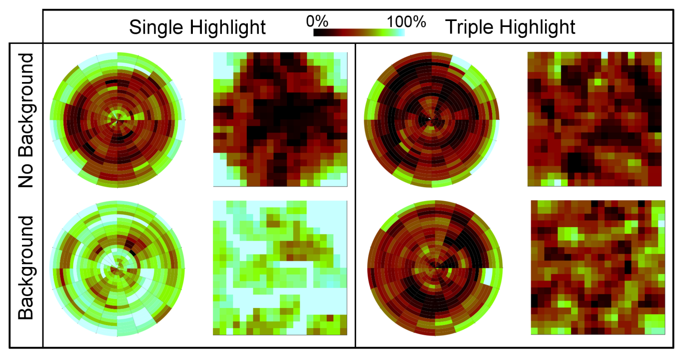

Fig. 10. Study II: Percentage of correct answers per cell, smoothed and split by experiment conditions.

These heatmaps, of course, also show the different difficulties of the conditions that we already observed in Figure 9. Apart from the overall color differences, we identify surprisingly different structures: While the border cells in visualizations without background patterns and single highlights clearly have high hit rates, the other three conditions do not show this pattern that obvious. Instead, the answer correctness is much more evenly distributed in these conditions. A reason for this effect could be that the additional context information that is available in these conditions might dominate the spatial effects that we observed and discussed in Section 4.2.3.

All in all, the result of this section confirms that providing visual context decreases the difficulty of the task, but more for Cartesian visualizations than for radial ones (Hypothesis 2). Since the availability of visual context significantly interacts with the coordinate system type, the question, however, arises whether there are similar factors that also influence the difference between Cartesian and radial visualizations.

5.2.2 Temporal Effects

Finally, we want to analyze the temporal effects—learning effects, etc.—that occurred in the second study. Figure 11 shows how the answer correctness values develop over time. To this end, we divided the experiment into its 20 parts, each consisting of a random permutation of the eight experimental conditions. Due to the only 21 participants, the values are still somewhat unsteady for a single part. To get more reliable results, we added a sliding average curve that summarizes the previous five parts for each data point.

The diagram indicates that there might be a learning effect during the first three parts, for Cartesian as well as radial visualizations. To

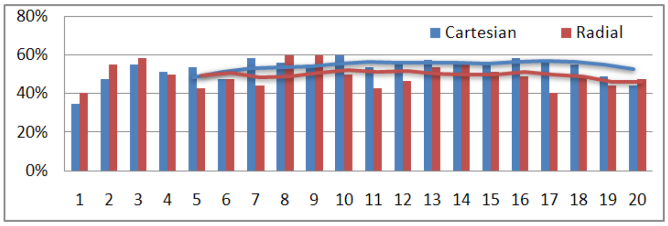

Fig. 11. Study II: Average percentage of correct answers over the 20 parts of the experiment with an additional sliding average over 5 parts.

test this observation, we again performed an ANOVA, here a two-way ANOVA with repeated measures considering coordinate system type and time segment (in form of the experiment parts). And indeed, the result considers the effect with respect to time segments as significant ($F_{1,19} = 5.718$, $p = 0.011$) and confirms the first part of Hypothesis 3.

Result 5. *There exist a learning effect in the first three parts of the experiment for Cartesian as well as for radial visualizations.*

When we further analyze the outcome of the ANOVA, we observe that the small difference between the Cartesian and radial visualizations in the first three parts does not get significant ($F_{1,20} = 2.642$, $p = 0.120$). And even more interesting, an interaction effect between coordinate system type and time segment in not plausible ($F_{1,19} = 0.049$, $p = 0.952$). This means that, in contrast to the second part of Hypothesis 3, a more intense learning effect for radial visualizations is unlikely.

Apart from the first three parts, Figure 11 documents nearly stagnating correctness values, especially when we look at the sliding average curves. But in detail, some minor effects show up: First, the Cartesian curve slightly rises until about half-time, while the radial curve does not change analogously. Second, both curves somewhat decline towards the end of the experiment. This might be caused by an incipient exhaustion of the participants or by anticipating the experiment end (the participants had been informed about the experiment length). But despite small differences, the learning curves of both visualization types are very similar in general.

Observation 8. *We observe similar temporal curves for Cartesian and radial visualizations.*

Summarizing the discussion on temporal effects, we were able to confirm a learning effect at the beginning of the experiment (first part of Hypothesis 3), but not a stronger effect for radial visualizations (second part of Hypothesis 3). The similar temporal curves for Cartesian and radial visualizations provide more evidence towards rejecting this second part. Nonetheless, note that a different learning effect would have questioned the results and observations of the first study to some extent: With just eight shown visualizations, the first study only hints at a small section of the temporal curve.

6 Discussion

We designed the two studies to uncover strengths and weaknesses of radial visualizations. In this section we want to analyze our contribution to this research question.

6.1 Threats to Validity

We reduced a complex research question to a simple task in a simple visualization. On the one hand, this is absolutely necessary to conduct a valid scientific experiment that is generalizable to some extent. On the other hand, it is questionable how far we depart from the original question and real-world applications by this simplification. The most important requirement is that the task as well as the visualization is generic. We thoroughly discussed this issue in Section 3.1. While we consider both to be generic, we do not claim them to be the only possible generic alternatives to test the hypotheses. Moreover, one cannot predict how a complex visualization would perform by simply adding up known empirical results for its visual elements. As shown in this study, interaction effects might also influence the performance (Result 4).

While we found several correlations, all discussions about cause and effect remain speculative—though, the simplicity of the experiments also reduces the number of possible causes.

We actually measured clicks at the right cells and not whether the user memorized the location correctly. Users might have memorized the wrong location, but accidentally clicked at the right cell, or they might have memorized the right cell, but accidentally clicked at a neighboring cell.

In detail, limiting factors of our visualization and task could be, the small number of cells (cells had to be clickable), timing parameters like presentation time and answer time, or shape and color of the cells. Although we set these parameters thoroughly, we cannot guarantee the elimination of all biases caused by them. As noted at the end of Section 4.2.1 a longer duration of the first study would have been preferable.

Another threat to the validity and, in particular, to generalizability of our findings is the choice of participants. While the participants of the first study rather represented the average computer user, those of the second study potentially had more expertise with information visualizations. In both studies the participants performed the experiments at their own computers. While this is certainly a more realistic environment compared to a laboratory study, we could not observe them during the experiments. Some might have used strategies or tools which distort their particular results. At least we guard against simple strategies like a finger tip on the highlighted cells on screen by moving the coordinate system. Finally, while we made sure, that the participants used a sufficient screen resolution, we could not control more sophisticated technical variable like mouse acceleration or screen contrast, and situational variables like viewing distance or noise disturbance. But since the we applied a within-subject experimental design, those interfering factors are not likely to bias the results towards Cartesian or radial visualizations. Moreover, in the first study, the large number of participants could compensate possible random biases by some participants.

6.2 Practical Implications

Our two studies yield a number of interesting results and observations. But from the perspective of a visualization designer, the central question is *what can we learn from these findings with respect to practical applications?*

Our findings suggest the following implications. Considering limited generalizability of our findings, we regard the guidelines as preliminary. To enhance their credibility, we suggest to conduct independent experiments that test these implications for a broader range of visualizations and tasks.

- *Use a Cartesian coordinate system unless there are clear reasons to favor a radial one* (Result 1 and Result 2).
- *Provide a recognizable local visual context, especially in Cartesian visualizations* (Result 3 and Result 4).
- *Encode the more important dimension in sectors, not in rings* (Observation 7).
- *Consider the dominating reading direction of your users in Cartesian visualizations* (Observation 6).
- *Use border areas for the most important information* (Observation 4).
- *Omit the innermost ring in radial visualizations, but do not refrain from using the other inner rings.* (Observation 5).

Although the data determines the final layout of a visualization, the visualization designer usually takes many design decisions. In these decisions the designer may consider the proposed guidelines. As an example, assume that we want to create a visualization of persons that participated in different tests; each person got a score from each test. This is a three-dimensional data set, which we could visualize using a two-dimensional coordinate system for persons and tests, and color for test scores. We now would have to choose between a Cartesian or a radial coordinate system. Applying our guidelines, we would use a

- *Cartesian coordinate system* when tests and persons are equally interesting. We would sort the most important tests to the left, or to the top respectively. We could add some visual context by using alternating background colors or by grouping similar tests.

- *radial coordinate system* when we want to focus on one dimension (e.g., persons), which would then be represented by circle sectors. We would sort the most important tests to the outer rings and leave the circle center blank.

Beyond these guidelines, the main research goal of this work was to contrast and compare Cartesian and radial visualizations. In particular, we wanted to analyze how our findings influence the design decision between the two visualization types.

We consider Cartesian visualization as the default choice because they tend to perform better with respect to perception accuracy (Result 1) and they clearly outperform radial visualizations with respect to perception speed (Result 2). Typically, they are also easier to implement and faster at runtime. Once more, we want to point out, that providing a visual context in Cartesian visualizations is very important because they lack of natural reference points, especially in the center of the visualization (Result 3 and Result 4).

Nevertheless, we think that radial visualizations are much more than just fancy versions of Cartesian visualizations. Although Cartesian visualizations showed better results in general, in some conditions radial visualizations outperformed their Cartesian counterparts (Observation 2). Moreover, we observed very similar temporal curves for both visualization types (Observation 8). But radial visualizations are particularly interesting when depicting two dimensions that are not equally important. We suggest to represent the more important dimension as sectors because memorizing sectors seems not only to be much easier than memorizing rings, but also than memorizing rows or columns (Observation 7).

Finally, we have to acknowledge that other factors also influence the decision that cannot be covered by our empirical approach. For instance, the Cartesian or radial layout might be the natural representation of a data set (e.g., Cartesian visualization for representing tables) or might provide a comprehensible metaphor (e.g., concentric circles could depict the degree of friendship in an egocentric social network). The designer of the visualization still has to consider these semantic aspects, but we expect our findings to alleviate the decision.

7 Conclusion

This study is a first step towards understanding differences of Cartesian and radial variants of information visualizations. We conducted two studies with different foci—a short study with broad participation and a longer study with potential expert users. Our results and observations indicate clear differences between Cartesian and radial visualizations. Cartesian visualizations tend to outperform their radial counterparts especially with respect to answer times. Nonetheless, radial visualization seem to be more appropriate for focusing on a particular dimension. Since we employed a generic visualization and task, we consider our findings partly generalizable. Our discussion on practical implications showed that we were able to provide some empirically tested insights to support the decision between a Cartesian and a radial coordinate system.

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