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Short Paper

Judgment Error in Pie Chart Variations

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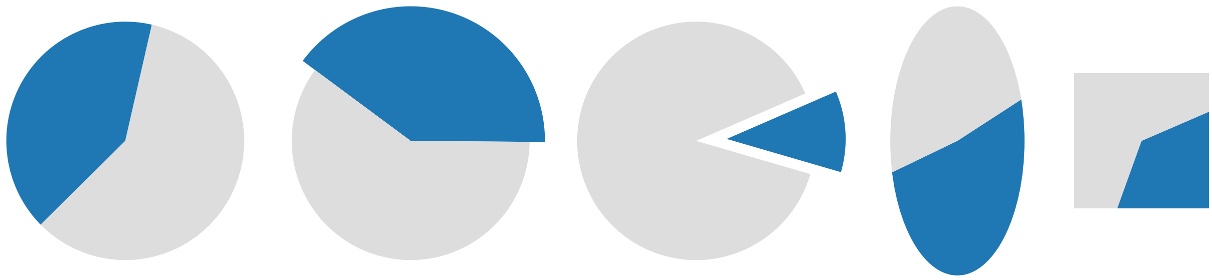

Figure 1: *We tested four variations on the basic pie chart to measure their effect on error in reading. Left to right: base pie chart, chart with larger slice, exploded pie, elliptical pie, and square pie.*

Abstract

Pie charts and their variants are prevalent in business settings and many other uses, even if they are not popular with the academic community. In a recent study, we found that contrary to general belief, there is no clear evidence that these charts are read based on the central angle. Instead, area and arc length appear to be at least equally important.

In this paper, we build on that study to test several pie chart variations that are popular in information graphics: exploded pie chart, pie with larger slice, elliptical pie, and square pie (in addition to a regular pie chart used as the baseline). We find that even variants that do not distort central angle cause greater error than regular pie charts. Charts that distort the shape show the highest error. Many of our predictions based on the previous study's results are borne out by this study's findings.

1. Introduction

Pie charts are a common feature in information graphics (infographics). Not content with regular pie charts, designers often modify them by changing their shapes, moving slices apart, or enlarging slices to emphasize them (Figure 2).

In a recent study, we found that contrary to common assumptions, central angle is likely not the primary way people read pie charts [SK16]. Area plays a significant role, and arc length may be involved as well (in particular when reading donut charts, which we found to perform no worse than pie charts). This leads us to predictions of the effect of pie chart design variations.

Based on these predictions, we designed a study that directly investigates four common variations of pie charts that are often used in infographics. The goal was to shed further light on the underlying mechanism that people use when reading pie charts. If they used central angle, their responses would be affected differently by these design choices than if they took area and/or arc length into account.

We also wanted to directly assess the impact of these design decisions on the readability of these charts, since they are intended to communicate data. If the ways they are rendered cause errors in the way people read them, they do not actually serve their purpose. Infographic designers currently don't have much research to base their designs on.

Of the four pie chart variations in the study (Figure 1), three change the relationship between angle, area, and arc length. The only one that does not is the exploded pie chart.

2. Related Work

Despite their popularity in business, pie charts have received very little attention from the academic community.

Work on pie charts' effectiveness is somewhat contradictory. Cleveland and McGill show that pie charts are less accurately readable than bar charts [CM84]. Other studies show a more nuanced picture, however. Simkin and Hastie demonstrate their usefulness

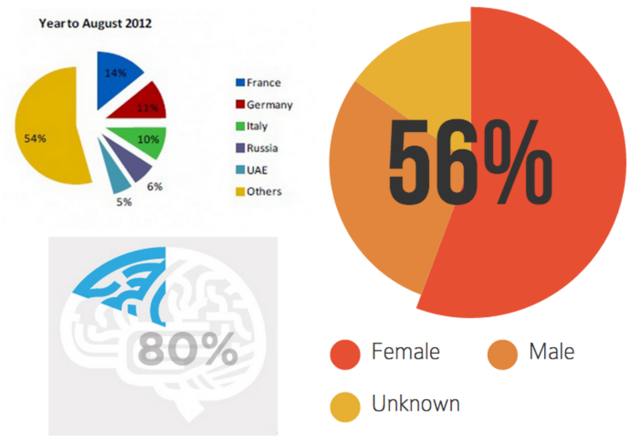

Figure 2: *Examples of pie chart variations from infographic repository Visual.ly [Vis15]: exploded pie chart, chart with a larger slice, and chart with a non-circular shape. These directly inspired the designs of the materials for the study reported here.*

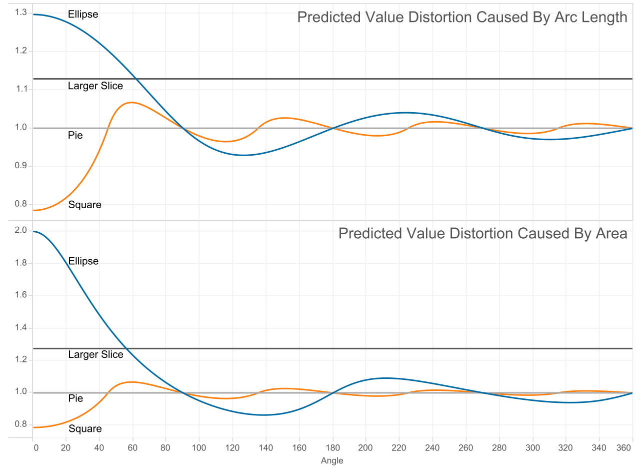

Figure 3: *The effect of arc length (top) and area (bottom) as a function of central angle, by variation type. The pie chart serves as a base line, the other values are expressed as multiples.*

for particular tasks, such as part-to-whole comparisons [SH87], while Spence and Lewandowsky find them superior to tables when it comes to quick comparisons [SL91]. Precision in reading pie charts was a topic of interest even before Cleveland and McGill: Croxton and Stryker performed similar studies in 1927 [CS27].

We have been unable to find much work that investigates the underlying mechanism of how we actually read pie charts, apart from our own. Books tend to state that we read the central angle, but not point to actual research. Only one article from 1926 directly investigated the perceptual mechanism. Eells measured people's performance reading pie charts and asked them to indicate the mechanism they thought they used: about half chose arc length, with about a quarter each picking area and angle [Eel26].

Distortions in pie charts are common in information graphics. A popular way of emphasizing a slice is to increase its radius so it sticks out. This is somewhat reminiscent of Nightingale's mortality ("coxcomb") chart [Nig58], though that chart did not use angle to encode data. We performed an informal survey of infographics posted on Visual.ly [Vis15] to pick common pie chart variations.

3. Materials and Procedure

Given the results of our previous study [SK16], we made predictions about the effects of common pie chart variations. The previous study was focused on decomposing pie charts into their visual cues. For this study, we modeled a number of simple charts on the most common design choices and distortions we found in infographics.

The set of stimuli to present to study participants consisted of the following pie charts and variations (Figure 1):

- *Baseline circular pie chart* with two slices: one gray, the other blue.
- *"Exploded" pie chart* with the blue slice moved away from the center. This does not change the angle, area, or arc length.
- *Larger slice chart*, where the blue slice had a larger radius than the gray one, making the blue slice stick out. The larger radius led to a larger area and arc length.
- *Elliptical chart*, compressed horizontally into an ellipse. This was done by masking out the unneeded parts of a full circle. We used a vertical ellipse rather than a horizontal one to minimize it being read as a 3D pie chart. The ellipse strongly distorts area and arc length, but not angle.
- *Square "pie chart,"* created by cutting a square out of the basic pie chart. Just like the ellipse, this has a nonlinear effect on area and arc length.

The study procedure was almost identical to our previous study. Participants were recruited on Amazon Mechanical Turk. They were first asked a set of basic demographic questions (10-year age group, gender, highest degree obtained), then they saw a brief description of the study with an image that showed them examples of all the different types of pie variations to expect in the study.

The body of the study showed them one chart at a time and asked them to estimate the percentage shown by the blue (darker) slice as a whole number. We used the same set of numbers as in our previous study; their values varied from 3% to 97%. The order of values and variations shown was randomized for each participant. Each chart was rotated at a random angle to avoid effects based on slice edges being aligned with major axes.

4. Predictions and Hypotheses

In a regular pie chart, area and arc length increase linearly with angle (both are fractions of the entire circle). When the shape is distorted or one section is larger, that relationship is more complicated. We calculated arc length and area as a function of central angle for the five variations we studied. Figure 3 shows them as a multiple of the baseline pie chart (which is identical with the exploded pie chart).

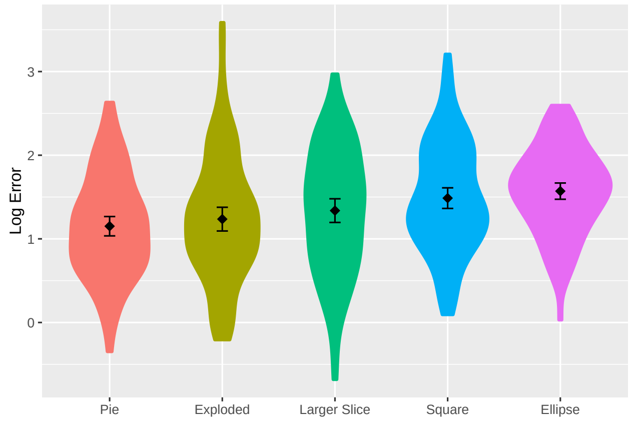

Figure 4: *Mean log error (dot) and distribution of log error of responses by chart type. Error bars show 95% confidence intervals.*

Chart Variation	Mean Log Error	95% CI
Baseline Pie	1.151	±0.098
Exploded	1.236	±0.101
Larger Slice	1.338	±0.096
Square	1.487	±0.097
Ellipse	1.570	±0.097

Table 1: *Means and 95% confidence intervals for log error by pie chart variation.*

The larger slice is a simple multiple, determined by the larger radius (175 vs. 155 pixels). The square's area was determined by adding up 45° increments, and then computing the final fraction's area as a right-angle triangle. Rotation was taken into account by calculating the area for the central angle plus the rotation (measured from the positive x axis) and then subtracting the area covered by the rotation angle. Similarly, the area of the elliptical chart was determined by adding up quarters of the ellipse and then adding the final part using the formula for ellipse slice area within a quarter ellipse.

Arc length was determined in a similar way. For the square, the length of the blue border was determined by adding up 45° sections (corresponding to half the length of a side) and then adding the fraction determined by the angle within the last octant. Arc length for the ellipse cannot be determined with a simple formula, and instead was computed using numeric integration of the path integral along the ellipse.

Based on these computations, we expected the following as compared to a basic pie chart:

- A chart with a larger slice should lead to systematic overestimation of the value, since the area of the slice is larger in relation to the rest of the pie than the percentage and central angle.
- For the exploded pie chart, we did not expect a difference, since the central angle is still as readable and there is no distortion of area or arc length.
- The ellipse distorts area and arc length, and presents more complex shapes. We therefore expected it to yield considerably higher error than the circular charts.
- The square is an unusual shape to use for a pie chart, and it also leads to a complex relationship between area, arc length, and angle, resulting in more error.

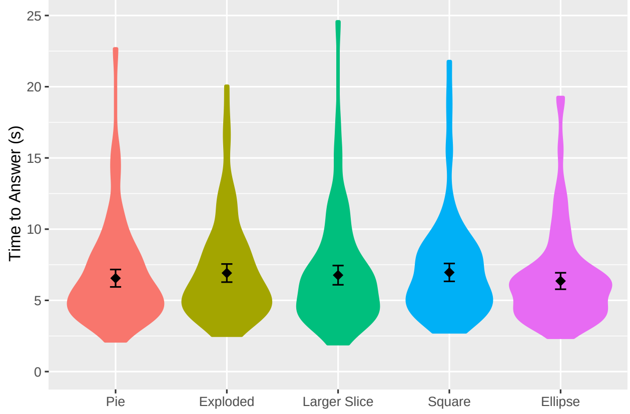

Figure 5: *Response times by chart type. Error bars show 95% confidence intervals.*

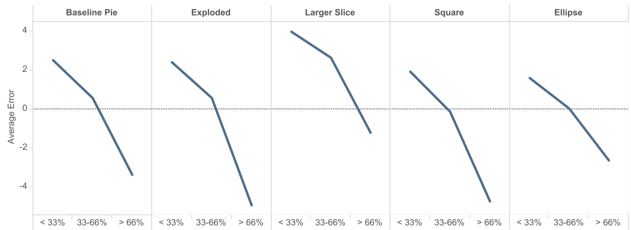

Figure 6: *Direction of error for each chart variation split into thirds: value $< 33\%$, $33-66\%$, and $> 66\%$. All variations lead to overestimation of small values and underestimation of large ones.*

5. Results

Of the 108 participants, exactly half were female. The predominant age group (43%) was 30–39 years old. High school or Bachelor's degree were reported as the highest degree by 44% each, with only 12% reporting a Master's or higher.

Participants completed the study in an average time of just over 11 minutes. They were paid $2 to participate, resulting in an extrapolated hourly rate of about $10.90.

We removed one participant's data from the analysis, since he apparently responded in degrees rather than percent. As in the previous study, we found a number of responses that appeared to be judging the wrong part of the chart. This was the case for 60 of 6420 total trials, or 0.93% of the data. In this case, we did not find any participants doing this consistently (the highest was 30% of answers), so we did not correct any of the data.

5.1. Judgment Error

The results are shown in Figure 4 and summarized in Table 1. As in the previous study, and for consistency with other work [HB10], we report the log absolute error, $log_2(|\text{judgedvalue} - \text{truevalue}| + \frac{1}{8})$.

There are considerable differences in error depending on the chart variation. They are visible in the distribution of error in Figure 4, and an ANOVA also shows them to be statistically significant ($F(4, 6415) = 12.071$, $p < 0.001$). The exploded pie chart has the second-lowest error, followed by the larger slice. The two charts distorting the shape had the highest errors, with the ellipse being even higher than the square.

Error varies by the angle presented, depending on the chart type (Figure 6). All charts lead to overestimation of small values and underestimation of large ones. On average, all but the larger slice chart lead to an overall underestimation of values. The larger slice chart leads to an overestimation by a factor of 1.6 on average. This is consistent with the idea that area plays a role (the area of the larger slice in our study materials was larger by a factor of about 1.28, which did not vary with the percentage shown).

5.2. Response Time

Time to answer does not differ between chart types (Figure 5). Only the square appears to be slightly higher than the others, but even that does not come near a statistically significant difference.

While we had not stated hypotheses for response time, we would have expected response times to be longer for the more unusual and harder-to-read charts, like the ellipse and the square.

5.3. Comparison with Predictions

Due to the small differences in the predicted effects of arc and area in our stimuli, we cannot decide which model is the closest fit. Using a linear model, we find multiple-R^2 values of 0.8839 for angle, 0.8731 for arc, and 0.8329 for area, respectively. Including the chart type, these increase to 0.8852 for angle, 0.8816 for arc, and 0.8693 for area. Despite these differences, all models have $p \ll 0.001$. We take this to mean that they all model the data very well and cannot be used to determine which visual cue is the most likely to be used to read the charts.

Regarding the qualitative predictions, we find that our results largely fit them:

- The larger slice leads to systematic overestimation over almost the entire range of values.
- The exploded pie chart shows higher error, which we did not expect. Perhaps the gap between the two slices adds a level of distraction that causes higher error.
- The ellipse yields much higher error than the circle, as expected.
- Likewise, the square produces larger error, just as expected. Interestingly, the ellipse actually leads to more error than the square, which we did not expect.

6. Discussion

Distorting pie charts has an effect on reading accuracy. All our variations increased the error. Even the seemingly innocuous exploded pie chart resulted in a measurable effect.

None of our designs changed the central angle, yet they all led to considerable error. This further undermines the importance of angle as the key visual cue, since angle was always easily readable.

What was distorted in all but the exploded pie chart was area and arc length. That led to more error. The systematic overestimation in the larger slice chart condition is particularly telling: the larger slice has more area and a longer arc, but covers the same angle. That said, we were unable to find a clear link between either area, arc, or angle and participants' responses that would have allowed us to decide which of the three was the most influential. This is somewhat consistent with our previous work, which suggested a combination of the three.

The increased error in the exploded pie chart was unexpected. One explanation is that the white space between the slices made it harder to estimate the total area of the pie. Moving a slice for emphasis is common in infographics and business presentations. Based on our results, it should be avoided, however. The pronounced effect of the square and ellipse shapes is also troubling. Shape distortions are quite common in infographics, and we found that they had the strongest effect among the variations we tested.

It is interesting to note that infographics often prominently include numbers on top of pie charts (Figure 2). This might seem to obviate the use of the chart in the first place, but the combination can be quite powerful. The pie chart, despite its distortion, still gives a rough idea of the differences, especially when they are large. The number then provides the precision that the chart does not. It seems that infographics designers are intuitively aware that their design decisions are impacting the precise reading of values.

The code used in this study and the resulting data are available at `https://github.com/dwskau/pie-variations`

7. Limitations

The effect of the distortions tested in this study is limited. We believe that we would have gotten stronger effects had we used a more compressed ellipse or a larger size difference for the larger pie slice. We picked those values based on charts we had seen in practice, however. While there are clearly exceptions, our distortions are in line with the more common ones found in information graphics.

8. Conclusions

Together with our previous paper [SK16], the results of this study call the assumption into question that pie charts are read primarily by central angle. If that were the case, error should not be different between the baseline pie and the exploded pie or the larger-slice pie. Both cause considerably higher error, though.

Design choices common in infographics cause considerable distortion. The worst offenders in our study were the ones where the shape of the "pie" was no longer a circle. We recommend that all such designs be avoided in favor of simple pie and donut charts.

Even seemingly innocuous changes, like moving a slice away from the center, can have an effect on error, however. Given the prevalence of pie charts in many different contexts, we believe that a more systematic study of these effects is called for.

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