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Arcs, Angles, or Areas: Individual Data Encodings in Pie and Donut Charts

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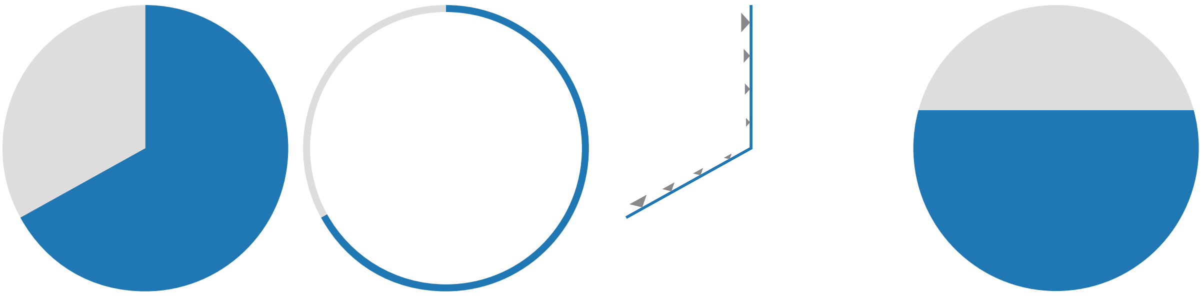


Figure 1: 67% encoded using different visual cues: angle, arc length, and area; just arc length; just angle; and just area.

Abstract

Pie and donut charts have been a hotly debated topic in the visualization community for some time now. Even though pie charts have been around for over 200 years, our understanding of the perceptual factors used to read data in them is still limited. Data is encoded in pie and donut charts in three ways: arc length, center angle, and segment area. For our first study, we designed variations of pie charts to test the importance of individual encodings for reading accuracy. In our second study, we varied the inner radius of a donut chart from a filled pie to a thin outline to test the impact of removing the central angle. Both studies point to angle being the least important visual cue for both charts, and the donut chart being as accurate as the traditional pie chart.

1. Introduction

Pie and donut charts are prevalent in all forms of communication with data, in particular when used as part of information graphics (infographics). In a random sampling of infographics on visual content website Visual.ly [Vis15], 36% of infographics with charts used some form of pie or donut chart. Information designers are experimenting with variations such as exploded charts, varying radius charts, icons broken into radial segments, nested donuts, etc. (Figure 3)

Despite their importance, the underlying mechanism of how we read those charts is not understood. This is partly because the visualization community tends to look down on pie charts and recommends against them. We are only aware of one study that looked into the perceptual mechanism of how people read pie charts, though it was based on people's own assessment. That study was published in 1926 [Eel26].

While angles are often mentioned when discussing pie and donut charts, there are three retinal variables that encode data: the angle, the area of the circle wedge, and the length of the segment on the circle (Figure 2). Which of these encodings do people read, and how important is their combination? Which can be left out without doing damage to accuracy?

To answer these questions, we designed a study to separate the three visual cues and compare how well each of them would do on its own (Section 3). Based on this, we then designed a second study to measure the difference between pie and donut charts and the impact of the size of the donut hole (Section 4). Both studies point to angle being less important than arc and area.

2. Related Work

William Playfair is usually credited with the invention of the pie chart, with his *Statistical Breviary* [PWS05] published in 1801 being the first known use of this chart type. The chart quickly took off, with Brinton complaining in 1914 about its use as a popular display for data [Bri14]. Today, virtually all charting and data analysis tools have the ability to create them, elementary school students are taught how to read and draw them, and they even appear in popular culture, making them a part of public consciousness.

2.1. Reading Accuracy with Pie Charts

Most research about pie charts looks to compare them to other chart types, primarily bar charts of varying configurations. This research has a long history, with some of the early work having taken place in the 1920s. Eells compared pie charts to stacked or "divided" bar charts and found that pie charts are more effective at helping the viewer determine the percentage of the whole [Eel26]. In response, Croxton and Stryker performed a study to settle the beginning dispute over the chart type, but ended up with a set of recommendations that varied by the number of pie slices, the values shown, etc. [CS27].

Cleveland and McGill's seminal work on graphical perception [CM84] addresses the effectiveness of different chart types, including pie charts, for different tasks. Despite referencing Cox's call for a theory of graphical methods [Cox78], and Kruskal's observation of the lack of theory or systematic body of experiment [Kru75], Cleveland and McGill stop at the evaluation of the charts' suitability for tasks and do not delve into the perceptual factors of the charts themselves. Cleveland also argues [Cle94] that pie charts are inferior for many common tasks because of *degraded pattern perception*, but does not provide a deeper explanation.

Simkin and Hastie [SH87] showed that pie and bar charts are equivalently suited for tasks involving estimation of the proportion of part to whole. Their work builds on Cleveland and McGill's, helping to establish the relative communication abilities for certain concepts of pie and bar charts, however it still does not look at the systems contributing to those communication abilities. Spence and Lewandowsky [SL91] also compared pie charts to bar charts and tables, this time using everyday tasks rather than simple magnitude judgements. They determined that pie and bar charts are definitely superior to tables, however their work still only compared chart types rather than exploring the charts themselves.

Very little work has dealt with donut charts. One study found no difference in precision between them [KZ10], though this was just a minor part of a larger study looking at various charts. They did find that people's confidence in their answers were higher for donut than for pie charts, however.

2.2. Perceptual Mechanism

One model of creating visualizations based on Wilkinson's *Grammar of Graphics* [Wil05, Wic10] argues that pie charts are stacked bar charts transformed into polar coordinates. Wilkinson does not claim that this is how they are actually read, but this view would suggest that the length along the outside arc is what people are looking at, not the angle in the center.

Most sources do not make explicit claims as to the way we read pie charts, and when they do they do not base them on research. Brinton [Bri14] implies that "circles with sectors" ought to be read by angle, but may mistakenly be read by area when images are inserted into the pie wedges. Bertin also claims angles as the main mechanism [Ber83], Robbins mentions angle judgments when reading pie charts [Rob13], and Munzner classifies pie charts as using the angle channel [Mun14].

The only study directly addressing the perceptual mechanism underlying the reading of pie charts we are aware of is Eells' 1926 paper [Eel26]. He lists the methods his study participants indicated as the ones they used "exclusively or predominantly": 51% reported using arc length, 25% area, 23% angle, and 1% chord length. The latter was the mechanism claimed by earlier work, which Eells clearly disproved. Kosslyn also points out the systematic underestimation of area in regards to pie charts, however the studies backing this up were not done in context of pie charts [Kos06].

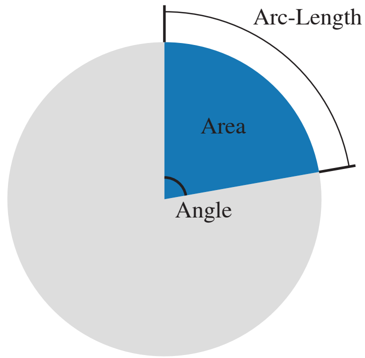


Figure 2: The three different encodings representing data in a pie or donut chart: central angle, wedge area, and arc length.

2.3. Use in Information Graphics

Pie and donut charts are very common in infographics, and are often modified from their canonical forms. We hope to use the results of this study to make recommendations about which of these are likely problematic, and which are probably no harder to read than regular pie charts.

Exploded pie charts (Figure 3a) don't directly violate any encodings, as all are individually present, however the arcs are no longer continuous. Varying radius pie charts (Figure 3b) do not maintain arc length and area encodings, though angle is not impacted. Charts constructed with icons (Figure 3c) often don't have accurate arc length or area encodings of the data. Nested donut charts (Figure 3d) make arc length harder to compare between the layers.

Depending on the significance of each encoding in the communication of data, these modifications to pie and donut charts may cause them to be significantly less effective. Indeed, our own recent work based on the results reported here [KS16] shows that exploded pie charts lead to higher error, as do larger radii – the latter cause systematic overestimation of the value. Shapes other than circles also predictably lead to more error.

(a) (b) (c) (d)

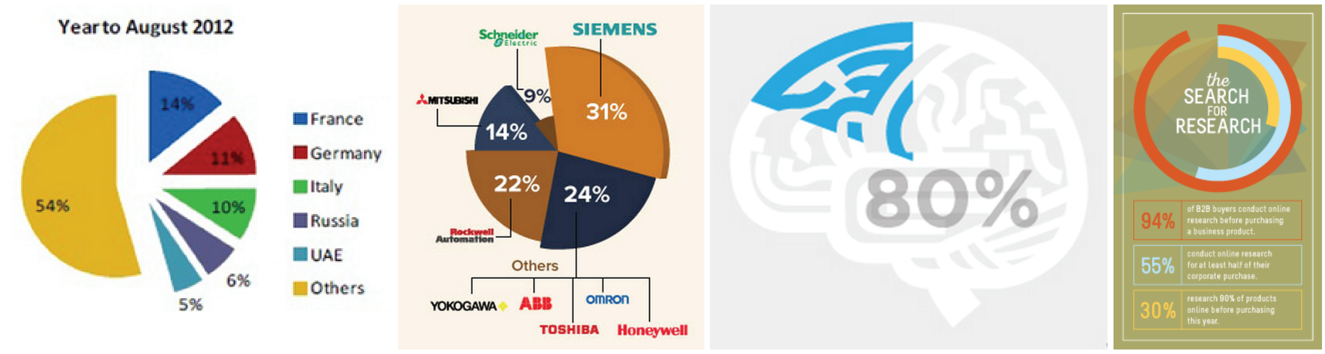
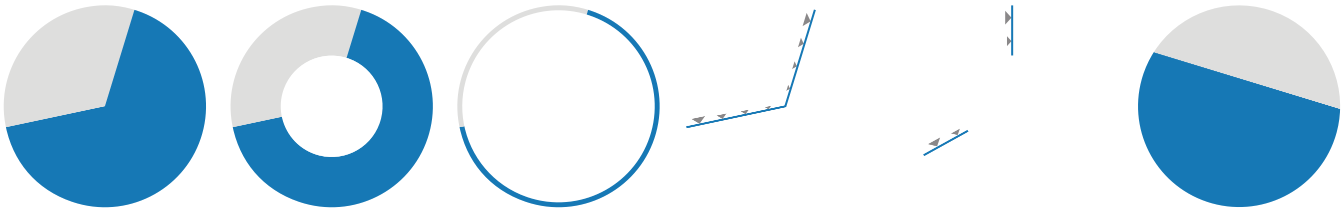
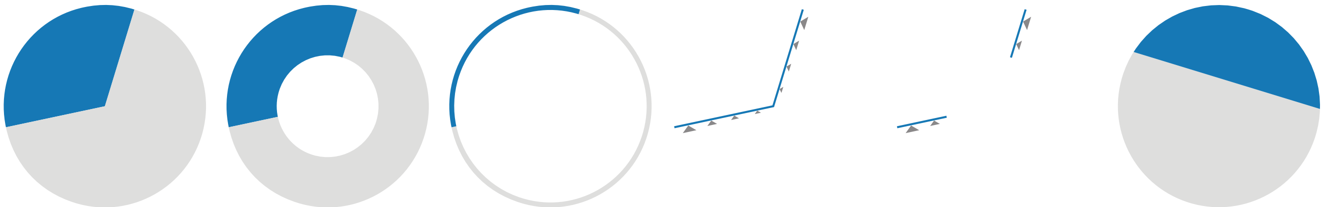


Figure 3: A sampling of pie and donut charts used in infographics, taken from examples found on Visual.ly [Vis15]. (a) exploded pie chart, (b) chart with varying segment radii, (c) pie chart constructed with an icon, and (d) nested donut chart.



(a) Pie chart. (b) Donut chart. (c) Arc length chart. (d) Angle pie chart. (e) Angle donut chart. (f) Area chart.



(g) Pie chart. (h) Donut chart. (i) Arc length chart. (j) Angle pie chart. (k) Angle donut chart. (l) Area chart.

Figure 4: A sampling of charts used in the study of pie and donut chart encodings. The top row all represent 67%, while the bottom row all represent 33%.

3. Study 1: Arcs, Angles, and Area Study

In order to test the contribution of each visual encoding, we designed new charts that allow us to isolate each retinal variable as much as possible (Figures 1 and 4). This allowed us to test the accuracy of arc length, angle, and area independently of their counterpart encodings.

We hypothesized that the baseline charts would be more accurately interpreted than any of the individual encodings, and the baseline pie chart would be the most accurately interpreted of all chart types. Of the individual encodings, we expected the chart type displaying arc length to perform the best because it is most similar to an extremely thin donut chart. We expected the angle chart for pies to be the next best performer, and then the angle chart for donuts.

However, we did not expect the individual encodings to perform much worse than the baseline charts. The rationale for this was that people presumably use a single cue to read a chart, rather than averaging from multiple ones.

3.1. Materials

The design of the test charts is key to being able to independently test the data encodings. Every chart has two segments. Pie charts “in the wild” often have more divisions, but we chose to constrain our stimuli to two parts to avoid complicating the task. In all of the charts, the blue portion is the segment referenced in the question (Figure 4). The rest of the charts are light gray, so the blue is the only color (and also darker), providing a clear focus and reducing distractions.

The study uses six different chart types (Figure 4):

- **Baseline Pie** – a standard pie chart (Figures 4a and g) using all three visual cues to represent the number.
- **Baseline Donut** – a standard donut chart (Figures 4b and h) using area and segment length to encode data. The angle is much more difficult to read due to the missing center where the lines would meet.
- **Arc** – a chart showing only arc length (Figures 4c and i), without area or angle.

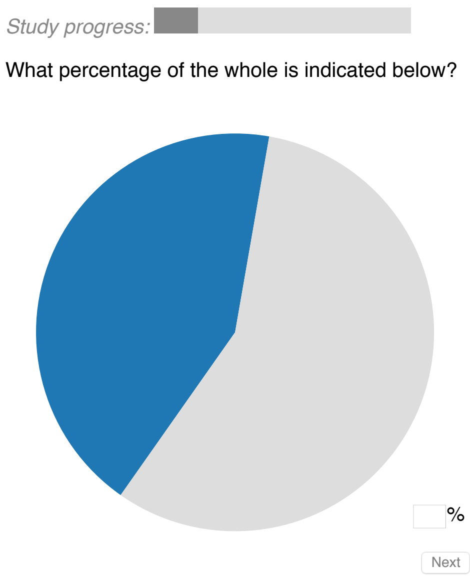


Figure 5: Screenshot of the survey showing a baseline pie chart.

- **Angle Pie** – a chart showing the angle component of a pie chart (Figures 4d and j) without a filled area or circle segment, thus removing these two cues. Little arrows point towards the part of the full circle that encodes the value from the outside.
- **Angle Donut** – a chart showing the angle component of a donut chart (Figures 4e and k), though without the lines meeting in the center that presumably allow precise judgment of the angle. Area and segment length are not represented.
- **Area Chart** – a chart using only area to represent a percentage value (Figures 4f and l). The area representing the data “fills up” proportionally as the value increases, thus removing angle cues and only providing very non-linear segment length.

Segment placement on all charts is randomized through a rotation of the entire chart to reduce the occurrence of segment edges that line up with quadrant points. This prevents participants from being able to use the natural quadrant points to gauge segment sizes.

Our experiment design is adapted from Cleveland and McGill [CM84] and Heer and Bostock’s replication of their study on Mechanical Turk [HB10].

Through a pilot study, we discovered some potential issues with a previous set of chart designs. We originally used a red dot outside the chart to indicate the focus area without interfering with the chart. This produced high error rates and caused confusion for the angle charts. In the pilot, it seemed that many participants answered for the opposite side of the angle charts. For example, if we asked about a portion that was 25%, their answer would be close to 75%. We were also concerned that the dot would make it easier to mentally complete the area or arc between the angle indicators in the angle-only condition, thus skewing the results. Using only color, we were able to point out the element of interest without adding extraneous objects. The angle-only condition is the only exception, but even then we kept the additional clues outside of the indicated angle.

Producing an angle-only condition requires extra marks in order to indicate which side of the angle the participant is supposed to answer for. We considered changing the question language to reference the side of the angle by its relationship to 180° (greater than or less than), however this provides non-visual information about the angle, and could confound results by introducing the concept of degrees.

The angle-only condition led to more opposite answers (about 10%) than the others (about 3%). The percentage is still relatively small though, and we accounted for most of the resulting error by flipping the answers for a number of users.

3.2. Procedure

The study consisted of six sections:

- Introduction page and brief demographic survey
- Pre-study questions about which encoding people thought they used to read pie and donut charts.
- Tutorial on how to read the more unusual chart variations
- Main part of the study asking for the values encoded in 48 different charts.
- Post-study questions about encodings used, same as in the pre-study part
- Short debrief

Introduction, Pre-Study, Tutorial

The study began with an introduction page followed by a short demographic form collecting education level, gender, age range, and physical monitor size. Every page after the intro page had a next button to advance to the subsequent page, with no controls provided to go back.

The first segment of the study included six questions broken up into two groups of three, one focused on pie charts, the other on donut charts (counterbalanced so some participants saw the donut chart questions first, others the pie chart). Each group began by asking the standard question for the study, “*What percentage of the whole is indicated below?*”, twice. The third question in each group asked the participant which encoding they thought they were using to come up with their answer, using a diagram similar to Figure 2.

A twelve-page tutorial section followed the first segment of the study. The tutorial explained each chart type, and asked two sample questions for each, with the answer shown as a hint. Participants had to enter that number in the response field to advance to the next page.

Main Section

After that, the main part of the study began. Each chart type was tested 8 times adding up to a total of $6 \times 8 = 48$ questions for each participant. A progress bar at the top of the page showed their progression through the study questions (Figure 5). After completing all questions in the body of the study, the first segment of the study asking about the individual encodings was repeated. This was done

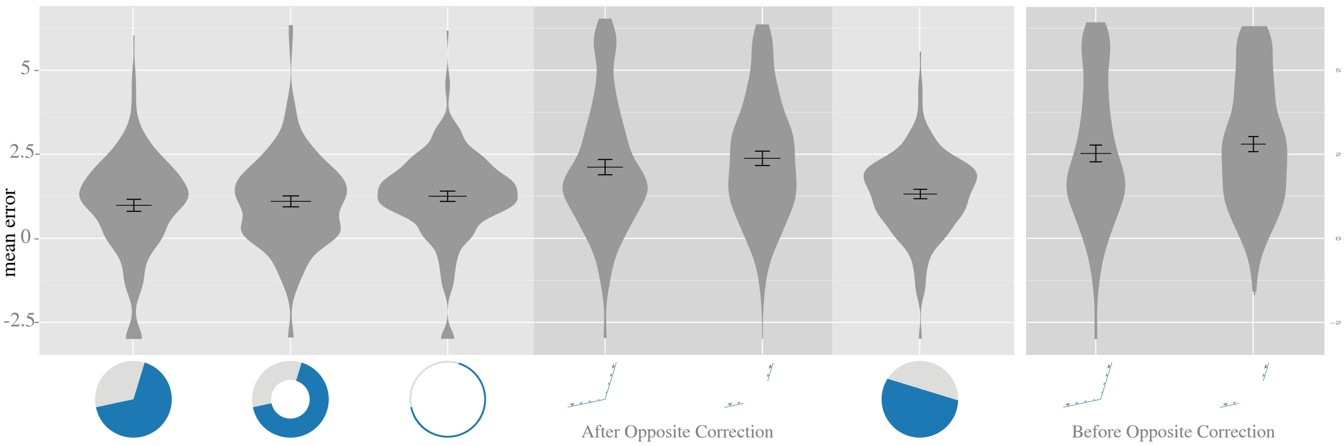


Figure 6: The distribution of amount of error per chart type after correcting for opposite answers on angle charts (uncorrected on far right). The error bars show 95% CI and the middle black lines represent the mean for each violin plot.

to see if participants would change their answers after having answered many more questions.

In the body of the study, charts were shown to participants in random order, however each chart type was shown eight times per participant. The data in the charts was from a pre-selected array of random integers with a possible range from 3 to 97, the same for every participant. The array was shuffled randomly for each participant, making any combination between data and chart type possible.

We asked the same question for every chart: "*What percentage of the whole is indicated below?*" Some of our chart variants made this relationship clearer than others. For example, the arc and area charts clearly have a part and a whole indicated by the blue segment and the gray segment, but the angle charts don't provide a good indicator of the whole. By keeping the question consistent and providing the brief tutorial at the beginning, we hoped to avoid confusion when participants encountered the more unusual charts.

Post-Study and Debrief

The study ended with a debriefing page explaining what the study was exploring and providing an optional free response form for feedback and comments.

For this experiment, we recruited 102 participants through Amazon's *Mechanical Turk* platform. We eliminated answers from two participants who did not complete the study. Subjects took an average of 25 minutes and 7 seconds to complete the study from start to finish, including the introduction and demographic form and a debriefing page with optional free response feedback. They were paid US$3.00 each for their participation, resulting in an average hourly rate of US$8.37.

3.3. Results

For the analysis, we edited one outlier value where a participant had entered 7068 and left a note about correcting this in the feedback

Chart	Mean	95% CI
Baseline Pie	1.032	±0.138
Baseline Donut	1.000	±0.137
Arc	1.294	±0.128
Angle Pie	1.967	±0.167
Angle Donut	2.279	±0.157
Area	1.306	±0.125

Table 1: Means and confidence intervals for log error by chart type (ANOVA: $F(5,4650) = 121.955, p < 0.001$).

section (we changed it to 70). We eliminated answers from three participants based on comments they left in the feedback form, which indicated that they had misunderstood the study or made major mistakes.

Five participants had answers that were wildly inaccurate, with three of them apparently answering in degrees instead of percentages. We omitted their answers from our analysis, leaving us with 92 participants: 43 female and 49 male, with the majority in the 25–29 and 30–39 age ranges.

Just as in our pilot study, pie and donut angle charts had issues with participants answering for the opposite segment in the chart. The occurrences of this were reduced from the pilot study, however it still happened often enough to merit correction. We measured the distance between the answer given and the value represented by the two segments in each angle chart. When over half of a participant's answers were closer to the opposite angle, we subtracted all of their answers from 100 to get their estimate for the opposite segment. We ended up doing this for 16 participants. The discussion below is based on the corrected results. We show both for the angle charts in Figure 6 (corrected in the main part, uncorrected on the far right).

For consistency with other studies [HB10], we report the log absolute error: $log_2(|\text{judgedvalue} - \text{truevalue}| + \frac{1}{8})$.

Figure 7: The distribution of error segmented by the percentage amount shown in each chart. All charts except the angle charts show an increase in error as the percentage shown in the chart increases.

Accuracy by Chart Type and Value

Means and 95% confidence intervals for log absolute error are reported in Table 1, violin plots of the same data are shown in Figure 6. We find these plots to be more informative than pure p-values, though we also report those in the table captions. Violin plots show the distribution of error better than box plots and others [CG14].

Error was smaller for the baseline charts, area chart, and the arc chart than the two angle-only charts. This was not what we hypothesized, and contradicts common wisdom that angles are critical to pie and donut chart perception.

Interestingly, the baseline donut chart had a slightly lower log error than the baseline pie chart, but well within the 95% confidence interval (virtually identical between the two).

The distribution of mean log error per participant in Figure 6 clearly shows the differences between the two angle charts and the other chart types. The relatively tall and skinny violin plots show a high degree of variance in the amount of error for the angle charts, while the other charts have relatively tight groupings, showing a consistent level of error. The arc-length chart has the tightest grouping of error, and despite a higher mean error, the amount a participant would be wrong by is be more predictable.

The unusual area-only chart has very similar error to the pie and donut. This is remarkable, given how difficult it generally is to correctly estimate area, and also the chart's lack of familiarity.

We found that the size of the percentage shown in a chart also has an impact on participant's ability to interpret the chart (Figure 7). All except the two angle-only charts show more error with larger segments.The two angle-only ones have a v-shape that has lower error for the middle third.

Accuracy by Self-Reported Main Visual Cue

At the beginning and end of the study, participants were asked to report which encoding they were primarily using to read pie and donut charts. The exact question was, *In the previous two charts, what did you primarily use to estimate the percentage?* Interestingly, our study had far more answers for area, while Eells [Eel26] found more people reporting the use of angle (Figure 8).

Mean log error per participant for each chart type segmented by their answers to the second self-reported encoding question suggests that there may be individual differences in people's ability to read angle, but the area and arc-length encodings help to reduce these effects (Figure 9). People who reported angle as their primary visual cue had lower mean error on the angle charts than people who reported arc-length or area, however they performed about the same for the other chart types. This suggests that people who believe they are reading angles may use them to interpret pie and donut charts, however people who believe they are reading arc-length or area are equally accurate with their preferred encodings. People who primarily use angles are able to use arc-length or area equally well for the charts where angle is not present. The mean error per person segmented by their primary visual cues are all the same, showing that arc-length and area are equivalent. In summary, angle encodings work well for some people, but arc-length and area work for all.

Demographics and Quadrant Alignment

We examined the data broken down by the demographic information provided, and found the expected effects of gender (males doing slightly better than females, also found by Eells), and age group (accuracy decreases slightly with age), but no discernible impact of highest degree completed.

The study was built to reduce the number of charts that would align with quadrants, however 300 (about 6.7%) of the charts did align on one of the quadrant edges due to random chance. We found no effect of this alignment on the results.

3.4. Discussion

Our results cast doubt on the importance of angle: angle-only charts both performed considerably worse than the rest. The possible impact of the chart design on the angle results does make it difficult to know whether the differences in their performance derive from the chart design or the encoding itself. This suggests that angle cannot be the only way we read a pie or donut chart. At least one of the other encodings is necessary to be able to interpret the angle encoding in a chart. We found that donuts are likely no worse than pies, despite missing the center. This suggests that area and arc length can make up for the missing angle information. While arc length and area alone are better than angle alone, they are still worse than complete pie and donut charts.

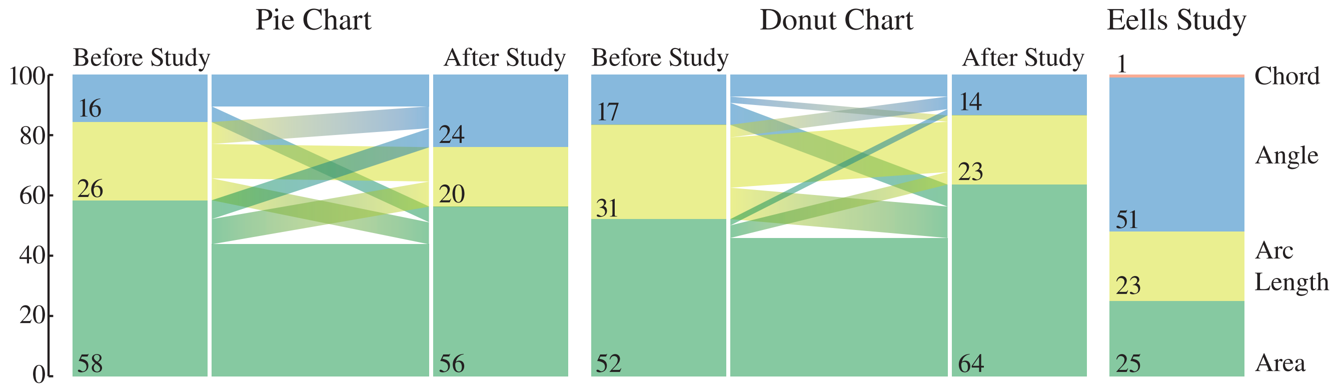


Figure 8: At the beginning and end of the study, participants were asked about the encoding they primarily used to interpret pie and donut charts. These are compared with self-reported answers from an earlier study [Eel26].

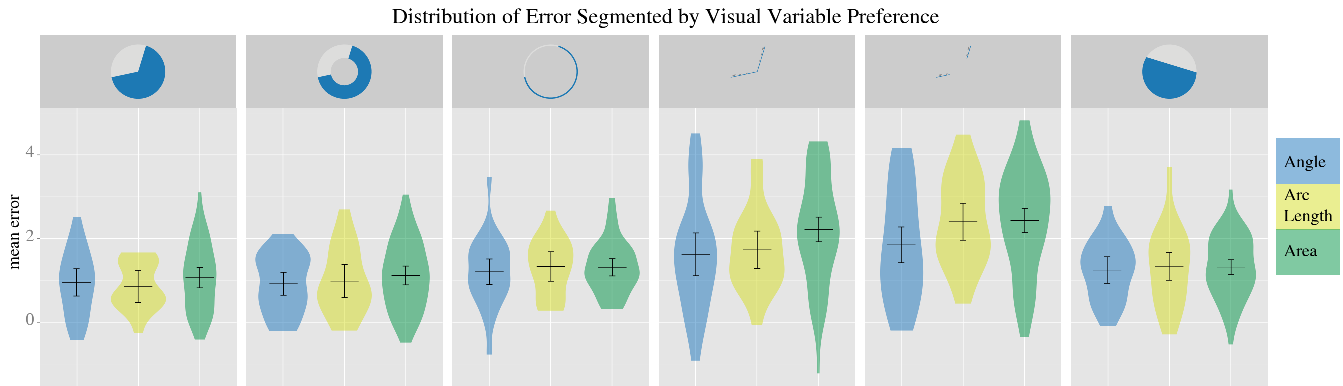


Figure 9: The distribution of error segmented by the second self-reported encoding preference for pie charts. People using angle did better in the angle-only condition than ones who reported using area or arc length. Black lines represent the means for each encoding preference per chart type, error bars show 95% confidence intervals.

Taken together, our results allow us to establish an ordering in terms of accuracy (with ≈ meaning "no different"):

- *baseline donut ≈ baseline pie*
- *arc ≈ area*
- *angle pie*
- *angle donut*

Encodings do not seem to combine in an additive manner. Instead, they appear to work together to substitute for the missing encoding when one is absent (as in the donut chart). Angle appears to contribute the least to the accuracy of the chart's communication. Arc length has a greater impact on the communicative value of the chart, however it still does not match all three encodings combined.

4. Study 2: Donut Radii

The results of the first study suggest that angle has a minimal contribution to our ability to perceive pie and donut charts. But within donut charts, does the size of the hole in the center make a difference? It should if angle is important, since any hole removes the most salient portion of the angle encoding: the center where the lines meet. Arc length is still present, as is area unless the donut gets extremely thin.

We therefore ran a study varying the inner radius of the charts from zero (i.e., a pie chart) to the point where only a thin outline was left. Our hypothesis was that the different inner radii would show no difference in how accurately they were interpreted. Based on the previous study's results, we expected the thinnest donut chart to have somewhat worse performance because of the higher error for the pure arc length compared to the donut tested there, but were unsure at which point accuracy would start to degrade.

4.1. Materials

We chose a set of six inner radii to ensure good coverage of the range of possible donut designs:

- 0% – a pie chart (Figure 10a)
- 20% – a small hole in the center (Figure 10b)
- 40% – a medium hole in the center (Figure 10c)
- 60% – a thick circle outline (Figure 10d)
- 80% – a thin circle outline (Figure 10e)
- 97% – a very thin circle outline (Figure 10f)

(a) Baseline pie chart; inner radius 0% of outer radius.
(b) Donut chart; inner radius approximately 20% of outer radius.
(c) Donut chart; inner radius approximately 40% of outer radius.
(d) Donut chart; inner radius approximately 60% of outer radius.
(e) Donut chart; inner radius approximately 80% of outer radius.
(f) Donut chart; inner radius 97% of outer radius.

Figure 10: The six inner radii tested in the second study, from a filled pie chart with no hole to a thin outline.

Throughout the study, the inner radius randomly varied among the six different sizes, however each size was tested ten times per participant. Just as in the first study, we chose to limit the charts to two segments to reduce distractions and focus the participant. The blue segments indicated the portion being asked about, while the gray segments indicated the rest of the whole.

4.2. Procedure

The structure of this study was similar to that of the first one. It was also posted on Mechanical Turk and ran entirely in participants' web browsers.

Like the previous study, it began with an introduction page followed by a short demographic form collecting education level, gender, age range, and physical monitor size.

This study did not include any tutorial, however, instead jumping straight into the chart questions. Each inner radius size was tested 10 times adding up to a total of 60 chart questions for each participant. The data in the charts came from the same pre-selected array of 60 random integers as in the previous study. The array was shuffled randomly for each participant, making any combination between data and radius size possible. Every chart was rotated at a random angle to reduce quadrant effects that make values at 25%, 50%, and 75% easier to perceive.

Just as in the first study, a progress bar at the top of the page showed their progression through the study questions. This study also ended with a debriefing page explaining what the study was exploring and providing an optional free response form for feedback and comments.

4.3. Results

Out of 117 recruited participants, 96 fully completed the survey in an average time of 15 minutes and 42 seconds. These 96 participants were compensated $2.00 each for an average of $7.85 per hour.

One participant appeared to answer in degrees rather than percent, so we discarded their responses. Two others had average log absolute error above 3.00 (the next highest was 2.27), which is why we also omitted their data. This left us with 59 male participants and 34 female participants, with the majority in the 25–29 and 30–39 age ranges.

We again use the log absolute error to report results. Figure 11 and Table 2 show that the distribution of log absolute error values across all inner radius sizes was very similar.

As in the first study, demographics had an effect on this study: males perform better across all inner radius sizes, and increase in error correlates with an increase in age.

4.4. Discussion

The results confirm that angle encoding, especially the center meeting point of the angle, is not contributing significantly to our ability to perceive pie and donut charts accurately. The lack of difference between the pie chart and all but the thinnest donut is also consistent with the first study.

The ratio of inner radius to outer radius on donut charts does not have a significant impact on the communication accuracy of a chart (with the exception of the thinnest one, which is somewhat less accurate). Although area encodings are technically preserved for all of the charts tested in this study, it is hard to imagine that the thinner donuts are being perceived using area, suggesting that arc-length may be the most important encoding in pie and donut charts.

5. Discussion and Recommendations

Infographic designers will not stop experimenting with pie and donut charts, however the results of our studies can provide some guidelines for their effective use.

Contrary to common wisdom, the angle is not the primary – and certainly not the only – factor when reading pie and donut charts. The center of the pie can be removed without affecting how precisely it can be read. The popular donut chart is thus no worse than the pie chart (though both are certainly less accurate than bar charts).

Icon based pie charts are also probably fine, as long as the icon's boundary is a circle with the same center point as the chart (Figure 3c is an example of an icon pie chart without a circular boundary). Exploded pie charts (Figure 3a) may be perfectly fine to use for some tasks, however they are likely detrimental to any tasks that involve summing of individual segments.

Our studies lead us to the following specific recommendations and observations:

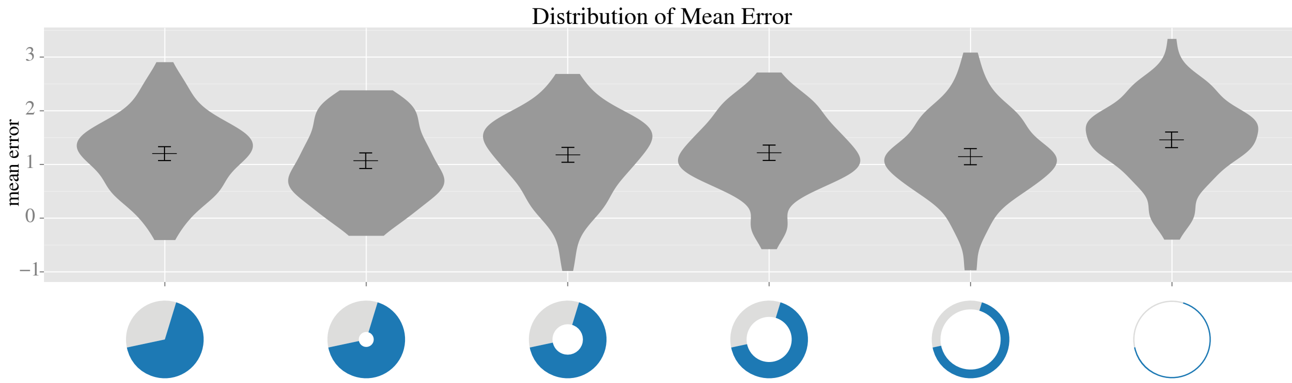


Figure 11: The distribution of amount of error per radius size. The error bars show 95% CI and the middle black lines represent the mean for each radius.

Inner Radius	Mean	95% CI
0%	1.327	±0.119
20%	1.162	±0.130
40%	1.289	±0.125
60%	1.333	±0.114
80%	1.257	±0.128
100%	1.553	±0.116

Table 2: Means and confidence intervals for log error by inner radius size (ANOVA: $F(5,5754) = 4.37, p < 0.001$).

- *Arc length is important*. It appears that changing the radius, whether based on data or just for aesthetic reasons (Figure 3b), interferes with people's ability to read the chart. This should be avoided.
- *Donuts are fine*. We did not find an adverse effect from removing the center of the pie.
- *Nested donuts (and radial bar charts) are problematic*. Since area and arc length are important, nesting donuts (Figure 3d) means comparing circles of different radius and area, which is likely problematic.
- *Keep cues consistent*. We did not test conflicting cues, but we have seen charts where the segments do not originate from the center of the circle (Kosslyn also mentions and recommends against them [Kos06]). Since more cues seem to make for better judgment, providing conflicting cues is almost certainly counterproductive.
- *Chart variations are possible*. Our minimal charts all performed quite well (compared to standard pie charts) and can serve as references for more artistic variations. The area-only chart in particular is surprisingly effective.

In the interest of reproducibility, all study code has been included as supplemental material. Materials and resulting data can also be found at https://github.com/dwskau/arcs-angles-area and https://github.com/dwskau/donut-radii.

6. Conclusions

Despite their bad reputation in data visualization, pie and donut charts are commonly used in information graphics and many other areas. Our studies attempted to find out which visual encodings are important for reading values off of these charts by splitting them into their constituent parts.

The results show that all three visual cues are important, but that arc length in particular seems to provide important information. Angle is clearly not a significant bearer of information in pie charts, and in particular the central meeting point of the circle segments does not appear to be crucial. Donut charts thus appear to be no worse than pie charts.

We also note that despite the generally firmly held stance against pie charts, little actual research has looked into their underlying perceptual mechanisms or the impact of design variations. Our own follow-up work to this study [KS16] has built on its findings and found further interesting results about such variations. More work is clearly needed, especially because of these charts' widespread use.

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