Geometric illusions in reading graphs

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The reading of a point on a graph is influenced by the slope of a line passing from the point in the direction of the calibrated edge against which the point is read. The sloping line is perceived to be too nearly at right angles to the calibrated edge. The direction of the error corresponds to the direction of the slope of the line; the size of the error increases with the distance of the point from the calibrated edge. A number of sloping lines lying between the point and the correct reading on the calibrated edge will increase the size of the illusion. The illusion is of about half the size of the conventional Poggendorff illusion.

Geometric visual illusions can occur in drawings of three-dimensional scenes, as well as in simplified line drawings (Gibson, 1950; Gregory, 1963). The investigations reported here show that geometric visual illusions can also occur in graphs. Other problems in the perception of graphs have been discussed by Kolata (1984).

Figure 1A illustrates the classic Poggendorff figure; Figure 1B illustrates an outside-in version of the figure, which resembles a graph. In both versions, the sloping line looks more horizontal than it is. If one rotates the page until the sloping lines are vertical, the two lines in Figure 1A are seen to be parts of the same line and the two dots in Figure 1B are seen to lie on extrapolations of the line. The apparent alignment disappears when the sloping line is not vertical or horizontal (Weintraub & Krantz, 1971, Figure 5).

The graph of Figure 2B corresponds to the left-hand portion of Figure 1B. The sloping line of Figure 1B corresponds to any one of the five functions of Figure 2B. The two vertical lines on the left of Figure 1B correspond to the ordinate and the column of five points just to the right of the ordinate.

In a figure containing only one function, there is only one point close to the ordinate. Therefore, there is no second vertical line just to the right of the ordinate. However, the Poggendorff illusion occurs with only one vertical line (Hotopf, 1981, Figure 6; Weintraub & Krantz, 1971, Experiment 3, Conditions 4 and 4c; Wenderoth, 1980, Table 2), although the illusion is smaller. A Poggendorff type of illusion has been reported without a vertical line (Day, 1973; Goldstein & Weintraub, 1972, Experiment 2; Wenderoth, 1980, Table 1).

Unfortunately, almost all investigations comparing different versions of the Poggendorff illusion have used

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Figure 1. (A) A classic Poggendorff figure. (B) An outside-in version that resembles a graph.

within-subjects designs. Thus, the illusion in a figure with no vertical line or with only one line, could be produced by transfer from prior judgments with a more complete Poggendorff figure (Poulton & Freeman, 1966; Warren & Bashford, 1977, p. 616). This would not be the case in Day's (1973) Experiment 2, which used only conditions without a vertical line. But even here, 4 of his 20 observers were familiar with the standard Poggendorff illusion, from having served in Day's Experiment 1.

In Figure 2B, any one of the sloping functions is perceived to be more horizontal than it is. This biases the

Figure 2. The two graphs used for very first judgments in Experiment 1. The functions are taken from Anderson (1972, Figure 1).

reading of the height of any point on the function made against the ordinate on the left. If the sloping function were taken to be horizontal, the reading would be far too low. In practice, the reading is only slightly too low, because the function is taken to be only slightly more horizontal than it is.

Figure 1B shows that there is a reverse effect if the height of a point on the function is read from the right-hand ordinate, as is possible in Figure 2A. If the sloping function were taken to be horizontal, the reading of the height would be far too high. But, because the function is taken to be only slightly more horizontal than it is, the reading is only slightly too high.

The illusion in reading the position of a point on a sloping line can be described by the following two rules: (1) The direction of the error corresponds to the direction of the slope of the line. (2) The size of the error increases with the distance of the point from the calibrated edge against which it is read. Rule 2 follows from Wenderoth (1980, Tables 1 and 2). Thus, in reading the height of one of the right-hand points in Figure 2A, the error will be larger when the height is read from the scale on the left than when it is read from the scale on the right. It follows that in order to minimize the error in reading, a point should be read from the nearest edge, whichever this is. Therefore, all edges should be drawn and calibrated, as in Figure 2A.

The illusion in reading from the abscissa of a graph is illustrated by a rotation of Figure 1B through 90°. The same two rules apply as for illusions in reading from the ordinate.

During the last 15 years, there has been an upsurge of interest in geometric visual illusions. In the conventional Poggendorff illusion, a number of factors have been reported to play a part in producing the illusion, in addition to Hotopf's (1966, p. 309) "regression to right angles" tendency (Day & Dickinson, 1976; Hotopf, Ollereanshaw, & Brown, 1974; Weintraub & Krantz, 1971; Weintraub, Krantz, & Olson, 1980). But interest has been concentrated largely on producing illusions and on discussing the possible mechanisms that may account for them. Little attention has been paid to presenting information in a way that avoids illusions.

Experiment 1 investigated the size of the illusion in a very first reading from Figure 2 in which different numbers of sloping lines crossed between the point and the correct reading on the calibrated edge. Experiment 2 investigated the illusion in a series of judgments, using single functions of different shapes.

EXPERIMENT 1 : VERY FIRST READING

Experiment 1 compared the very first readings of separate groups of observers, before the readings could be biased by transfer from illusions affecting prior readings. The observers had to read the height of one of the right-hand points in Figure 2. The control observers were

given Figure 2A, with the four calibrated edges. Thus, they could read the height of the point by using the calibrated edge just to the right of the point. If they did use the right-hand scale, their readings should have been slightly too high.

The experimental observers were given Figure 2B, with calibrated edges only on the left and at the bottom. Thus, in reading the height, they had to use the calibrated edge on the left, which should make their readings considerably too low. Perhaps the most sensitive test of the illusion could be made by comparing the predicted low readings of the experimental observers with the predicted high readings of the control observers.

One group of experimental observers read the height of the top right-hand point in Figure 2B. For them the point lay on a function that sloped down toward the calibrated edge at an angle of about 30°. There were no sloping lines crossing between the top right-hand point and the point at the same height on the scale. Another group of experimental observers read the height of the middle right-hand point. For them there were two sloping lines crossing between that point and the point at the same height on the scale. A third group read the height of the bottom right-hand point. For this group there were four crossing sloping lines, although there did not appear to be that many.

Method

Observers. The 94 observers, 75 women and 19 men, were members of the Applied Psychology Unit subject panel. Their ages ranged from 20 to 67 years, median age 45. The results of two additional women, 57 and 61 years old, were discarded. One woman apparently failed to understand decimals. She did not respond to the practice test, and did not use decimals in the experiment. The other woman gave the height of the point as 5.6 ft, presumably above the floor.

Procedure. The observers were tested in groups of between 9 and 16. They sat between 3 and 6 m from a screen. The figure on the screen measured about 1.3 × 1.3 m.

The height of the point had to be read to the nearest decimal point. Some observers were not familiar with decimals. They were all taught, using the analogy to pounds as units and pence as decimals, like dollars and cents. To check their understanding, they were then shown a practice slide exactly like the one on which they were to be tested, but with only a single point visible somewhere near the middle. They were asked to read the height of the point, and to write it down on the back of the answer sheet. They then compared their answers. For the control condition with four calibrated edges, all but three of the observers' readings fell within a range of .5. For the experimental condition with only two edges, all but two of the readings fell within a range of .9.

The observers were then shown the five functions in Figure 2, but without any edges visible. The investigator pointed to the height of the point that each observer had to read. One-third of the observers in each group had to read the height of the top right-hand point. Another third had to read the height of the middle right-hand point. The remaining third had to read the height of the bottom right-hand point. The point to be read was also indicated on the answer sheet.

Finally the slide corresponding to Figure 2A or Figure 2B was projected. The slide was left on until everyone had written down his or her answer. The times ranged from 20 to 50 sec for different groups of observers.

Results

The three rows of Figure 3 show the distribution of the errors, grouped in bins of .3, in reading the heights of the right-hand points of Figure 2. Readings within $\pm .1$ of the correct height were plotted as correct. The unfilled circles represent the control condition of Figure 2A, which had four calibrated edges. The observers could read the height of their points from the scale just to the right. If they used the right-hand scale, their readings should be increased slightly by the illusion illustrated on the right side of Figure 1B. Figure 3 shows that most of those readings are either correct or slightly too high. None of the averages of the 3 points is reliably positive on a two-tailed Wilcoxon test. There are three very large errors, shown on the left of the figure. Here the observers could have read the height of the wrong point.

The filled circles represent the illusion condition of Figure 2B, with only the left and bottom calibrated edges visible. Most of the readings were too low. The averages of the middle and bottom right-hand points are both reliably negative on a two-tailed Wilcoxon test ($p < .001$). The average of the top right-hand point is not reliably different from zero. However, for each of the three points, the illusion condition gave smaller average readings than did the corresponding control condition. All three differences are reliable at the .05 level or better on two-tailed Mann-Whitney U tests, even when the three very large control-condition errors are included.

Consider reading the height of the top right-hand point of Figure 2B against the calibrations on the left-hand ordinate. There are no sloping lines lying between the point and the point at the same height on the scale, whereas

in reading the height of the middle right-hand point, there are two sloping lines in the way. In reading the height of the bottom right-hand point, there are four sloping lines in the way. These sloping lines increase the size of the geometric visual illusion illustrated in Figure 3. The readings of the heights of the middle and bottom right-hand points are both reliably more biased by the illusion than are the readings of the height of the top right-hand point ($p < .02$ or better). However, there is no reliable difference in the size of the illusion between the middle and bottom right-hand points. Having four sloping lines in the way is not reliably worse than having only two sloping lines in the way.

Discussion

In this experiment, the observers were given as long as they needed to make their reading, and were encouraged to be as accurate as possible. Yet they showed a consistent geometric illusion in reading the heights of the points on the extreme right of Figure 2B, points which had to be read from the distant calibrations on the left. The illusion was greater for the middle and bottom right-hand points, where sloping lines lay between the points and the points at the same height on the calibrated scale.

The result for the middle right-hand point of Figure 2B was later replicated using as observers 20 members of the M.R.C. Applied Psychology Unit. The members made their readings just before a talk on this work with the advertised title "Geometric illusions in reading graphs." In spite of the warning given by the title, the average reading was reliably too low ($p < .001$).

In Figure 2A, the heights of the extreme right-hand points can be read from the calibrations just to the right of the points. Figure 3 shows that this produces a relatively small illusion in the direction opposite to that of the illusion of Figure 2B, as could be predicted from Figure 1B. The illusion is smaller and not reliable because the points lie closer to the calibrated edge.

How do the mean constant errors (CEs) in the readings of Figure 2B compare in size with the errors for a Poggendorff illusion with two, one, or no vertical lines? The mean CEs in the illusion condition for the top, middle, and bottom right-hand points are, respectively, $-.20$, $-.65$, and $-.84$. The mean for the members of the Applied Psychology Unit was $-.42$. The mean CEs need to be corrected for the arbitrary size of the units on the ordinate of Figure 2; the most appropriate correction is probably to express each mean CE as a proportion of the difference in height between the right-hand point and the point where the extrapolated function crosses the left-hand ordinate. The proportional mean CEs are, respectively, -2.3% , -8.9% , -10.8% , and -5.7% (average -6.9%).

The mean CEs in the control condition shown in Figure 2A are a good deal smaller. When the three outlying points on the left of Figure 3 are excluded, the mean CEs are $+.15$, $+.20$, and $+.06$. The correction for proportionality is also smaller: the change in height between the right-hand point and the point where the extrapolated func-

Figure 3. Errors in the very first reading of the height of a point in Figure 2. The three rows represent, respectively, readings of the top, middle, and bottom right-hand points. Unfilled circles: control condition of Figure 2A, with four calibrated edges. Filled circles: illusion condition of Figure 2B, with only the left and bottom calibrated edges. M = median.

tion crosses the right-hand ordinate. The proportional mean CEs are respectively, +8.7%, +13.7%, and +3.8% (average +8.7%). When the sign is reversed, the average proportion is much the same size as the experimental average of -6.9%. This is what one might expect. The mean CEs are a good deal smaller, but so is the change in height over which the illusion is measured.

The proportions can be compared with Weintraub and Krantz's (1971, Figure 1) fitted proportion of -16.2% for the conventional Poggendorff illusion, shown in Figure 1A, with the two parallel lines vertical. In Weintraub and Krantz's investigation, the slope of the line and the size of the gap between the two vertical parallel lines were varied systematically. As in the present investigation, each of Weintraub and Krantz's 850 observers made only a single judgment, so there was no possible chance of bias from prior judgments. The -16.2% represents the mean illusion (measured in millimeters) divided by the true change of height (in millimeters) of the course of the sloping line between the two parallel lines. The proportion is about twice the average proportions calculated from Experiment 1 (-6.9% and +8.7%).

Similar proportions can be calculated from Wenderoth's (1980, Tables 1 and 2, Single 1 and Double 1 conditions) measurements of Poggendorff-type illusions with a sloping line of 45°. Wenderoth's changes in height can be taken to extend from the top of his sloping line to the correct height of the dot whose height was adjusted. Wenderoth's average proportions were -2.8% and -7.9% for no vertical line, -17.1% for one vertical line, and -21.9% for two parallel vertical lines. The range of values covers the range found in Experiment 1 and extends upward beyond Weintraub and Krantz's -16.2%. Unfortunately, Wenderoth's results all came from the same 13 students, and were therefore likely to be biased by transfer between conditions (Poulton & Freeman, 1966).

EXPERIMENT 2: MULTIPLE READINGS

Experiment 2 investigated the geometric illusion using four simple graphs of different shapes. Each observer made a number of readings of each graph. It was predicted that four of the readings would be biased by the illusion. As with Experiment 1, perhaps the most sensitive test of the illusion could be made by comparing the four readings that should be biased by the illusion with the corresponding readings from the graphs with four calibrated edges, which should be slightly biased in the reverse direction.

Method

Observers. The 12 observers, 10 men and 2 women, were all members of the Applied Psychology Unit at Cambridge. Their ages ranged from 22 to 57 years, median age 44. All were used to reading graphs. None knew the purpose of the experiment.

Graphs. The eight graphs are illustrated in Figure 4 without the labels and the numerical values (in 10s) that were printed on the originals along the calibrated edges. The control graphs in the bottom row had four calibrated edges. The experimental graphs in the top row had only two calibrated edges, one on the left and one at

Figure 4. The eight graphs used in Experiment 2. In the originals, each calibration mark on the edges has a number between 10 and 90 printed against it. Each vertical edge is labeled SECONDS in capitals. Each horizontal edge is labeled CENTIMETERS. The points at the ends of the four dotted lines show the mean sizes of the CEs whose directions are predicted. The dotted lines are not present in the originals. For Graph 8, the small mean CE is in the opposite direction to that predicted.

the bottom. In the originals, the vertical calibrated edges were all labeled SECONDS in capitals. The horizontal calibrated edges were all labeled CENTIMETERS.

The graphs were drawn on tracing paper with a black ballpoint pen and were mounted on square white cards measuring 17×17 cm. The edges of the graphs were 9 cm long. For the control graphs in the bottom row, Points A and C were always 1.27 cm from the nearest two edges. Point B was always 2.54 cm from the nearest two edges. All the line segments were 5.25 cm long. They sloped at angles of 14° to the horizontal or vertical. Each experimental graph in the top row of Figure 4 had the same dimensions as its control graph (pictured in Figure 4 directly below the experimental graph).

The within-subjects design presented problems in selecting the calibrations for the edges. The experimental and control readings had to be comparable, but not identical. Therefore, we made the readings of the units the same in the experimental and control graphs, but varied the 10s from graph to graph. The correct readings in units never involved 0 and 5. The 10s all lay between 10 and 90.

Procedure. The 12 observers were tested individually. Each observer served in three sessions of about 3 min each, on 3 consecutive half days. In one session, readings in both dimensions were made on the A points of the eight graphs. Another session involved the eight B points, and a third involved the eight C points. The order of the points A, B, and C was varied irregularly from observer to observer, but 7 observers started with point B.

The eight graphs were always presented in the order 1, 5, 4, 7, 3, 6, 8, 2, which was taken from a table of random numbers. Of the first five graphs, only Graph 4 had two edges. Within sessions, this reduced the chance that the practice of using exclusively the left-hand and bottom edges would transfer from the graphs with two edges to the graphs with four edges.

One graph at a time was placed, covered by a card, on a table in front of the observer. When the observer indicated that he or she was ready, the card was removed for 2 sec and then replaced. The observer then had to call out the readings corresponding to the point, in the order y then x, to the nearest digit (e.g., 68, 51). The experimenter recorded the responses.

Results

Errors in tens. About 7% of the readings had errors in the 10s, the errors ranging from +40 to -66. All but 3 of the 12 observers made errors in reading the 10s.

These large errors were apparently distributed at random and were split pretty evenly between the graphs with two and four edges (18 and 22 errors, respectively). There were 21 large errors on the x axis and 19 on the y axis. There were 5 large errors in the readings with predicted illusions, and 3 in the corresponding control readings.

The errors in the 10s were probably due to the observers' concentrating on reading the digits in the 2 sec they were allowed, and not paying sufficient attention to the 10s. Proactive inhibition from previous readings then produced the errors in the 10s. Thus, the errors in the 10s are not likely to have been caused by geometric illusions. In addition, the errors in the 10s were not comparable for the illusion and control conditions, because the calibrations of the 10s differed between the experimental and control graphs. For these two reasons, the errors in the 10s were excluded from the analyses. The errors in the 10s were corrected to minimize the sizes of the digit errors. Thus an error of ± 10 was called 0, an error of $+21$ or -19 was called $+1$, an error of $+28$ or -32 was called -2 , and so on.

Errors in units. There are four points in Figure 4 whose readings in units should have shown an illusion. The points are indicated by the dotted lines, which show the mean sizes of the CEs found in the units. Three of the four mean CEs were in the predicted directions, and the combined mean CE of all four points confirmed the predictions. But the small mean CE in Graph 8 was in the opposite direction to that predicted.

The analyses of the errors in the units are given in Table 1. On the basis of the predictions made, there are two points whose average readings should have been increased by the illusion. In Graph 4 of Figure 4, Point A should have shown an increased reading in the horizontal, or x, dimension. In the table, the reading is listed as 4Ax. Similarly, the reading 4Cy should have been increased by the illusion. As expected, the table shows that for the reading 4Ax, the mean CE ($+1.77$, SE $.77$) is reliably positive on a two-tailed Wilcoxon test. For the reading 4Cy, the mean CE ($+1.00$, SE $.64$) is too small to be reliable. But when the mean CEs of the two readings are averaged for each of the 12 observers, as shown in the third row of Table 1, the average mean CE ($+1.38$) is reliably positive on a two-tailed Wilcoxon test.

Column 7 of Table 1 gives the mean CEs for the two corresponding control readings, 3Ax and 3Cy, from the

graphs with four calibrated edges. If the readings were made from the closest calibrated edges, Graph 3 of Figure 4 suggests that they should be slightly too small. The observed mean CEs are both small and unreliable.

The right-hand section of Table 1 gives the differences between the illusion and control readings. The difference between the mean CEs of 4Ax and 3Ax is reliably positive, but the difference between 4Cy and 3Cy is not. However, when the average mean CE of the two illusion readings is compared with the average mean CE of the two control readings, the difference ($+1.26$) is highly reliably positive.

Figure 4 suggests that readings 6Ax and 8Ay (in Rows 4 and 5 of Table 1) should be decreased by the geometric illusion. For the reading 6Ax, the mean CE is negative, as predicted, although not reliably. For the reading 8Ay, the mean CE is positive, although again, not reliably. For the two corresponding control readings, 5Ax and 7Ay, the mean CEs are also small and unreliable. However, as the right side of Table 1 shows, the difference of -1.42 between the mean CEs of reading 6Ax and the corresponding control reading 5Ax is reliably negative, as predicted.

The bottom row of Table 1 combines the four predicted illusions in Figure 4. The overall effect was calculated by subtracting the average mean CE for the two predicted decreases from the average mean CE for the two predicted increases, and dividing the remainder by 2. The mean difference $+ .67$ is reliable ($p < .05$). When the small reversed overall mean effect on the control readings ($-.13$) is subtracted from the mean difference of $+ .67$, the resulting mean CE ($+ .80$) is rather more reliable ($p < .02$).

In Figure 4, the B points all lie at the junction of two line segments. Thus, no predictions were made about possible illusions. When the readings are compared with the control readings, there are no reliable effects.

Discussion

Experiment 2 showed that the geometric illusion affects a series of readings of simple graphs of different shapes. The illusion is not restricted to the very first reading, or to graphs with almost parallel functions, like those in Figure 2. Thus, the illusion probably applies to the reading of all graphs with only two calibrated edges.

As in Experiment 1, the mean CE produced by the illusion can be corrected for the arbitrary sizes of the units

Table 1
Experiment 2: Errors in Units

Illusion					Control				Illusion Minus Control	
Reading	Prediction	Mean CE	SE	p*	Reading	Mean CE	SE	p*	Mean CE	p*
4Ax	Increase	$+1.77$	$.77$	$< .02$	3Ax	$-.43$	$.86$	-	$+2.20$	$< .05$
4Cy		$+1.00$	$.64$	-	3Cy	$+.67$	$.65$	-	$+.33$	-
Average		$+1.38$		$< .02$		$+.12$		-	$+1.26$	$< .001$
6Ax	Decrease	$-.67$	$.40$	-	5Ax	$+.75$	$.55$	-	-1.42	$< .02$
8Ay		$+.75$	$.95$	-	7Ay	0	$.35$	-	$+.75$	-
Average		$+.04$		-		$+.38$		-	$-.34$	-
Average	Increase - decrease	$+.67$		$< .05$		$-.13$			$+.80$	$< .02$

Note—Reading 4Ax indicates Graph 4, Point A, dimension x. *two-tailed Wilcoxon tests.

selected for the graphs. This is done by expressing the mean CE as a proportion of the change in height, or horizontal distance, of the sloping function. The measurement is made between point A or point C and the point where the extrapolated sloping function crosses the left-hand or bottom scale. The overall average mean CE for the illusion (+.67) thus becomes +7.6%. When the sign is reversed, this average proportion is much the same size as the average proportion of -6.9% found in Experiment 1. After correcting for the change in height or horizontal distance, the overall small reversed illusion of the four control readings in Table 1, -.13, becomes -12.3%. As in Experiment 1, the reversed illusion is much smaller than the overall experimental illusion (+.67), but so is the change in height or horizontal distance over which the illusion is measured.

GENERAL DISCUSSION

The results in Figure 3 and Table 1 show that there can be reliable geometric illusions in reading graphs. An illusion occurs when a point is read against a distant calibrated scale and the point lies on a sloping line that runs towards the scale. The bias can be greatly reduced by reading the point using a nearby calibrated scale. Thus, in order to minimize the illusion in reading a graph, the calibrated scales should be drawn as close as possible to the points. This means using four calibrated edges, as shown in Figure 2A. Readers should be warned of the bias that can be introduced by reading from a distant scale instead of using the nearby scale.

The results are probably most relevant to readers who glance casually at a figure. Their perceptual errors are likely to be considerably larger than the errors recorded in the present investigation, in which the observers took pains to respond as accurately as possible.

To estimate the extent of the problem, a survey was made of the main psychology journals published during the second half of 1983. The criterion was the percentage of all articles with graphs that had at least one graph with four calibrated edges—not a very strict criterion.

Of the articles in *Perception and Psychophysics* that had graphs, only about 25% presented a graph with four calibrated edges. This is fairly typical of American psychology journals. *The Journal of the Acoustical Society of America* had one of the highest percentages. In the Speech Communication, Psychological Acoustics, and Physiological Acoustics sections combined, about 55% of the articles with graphs had at least one graph with four calibrated edges. This is presumably due to the influence of the physicists. In *Vision Research* and in *Perception*, less than 15% of the articles with graphs had a graph with four calibrated edges.

Five journals had no graphs at all with four calibrated

edges. Two of these were the *British Journal of Psychology* and the *Quarterly Journal of Experimental Psychology*. Curiously enough, the other three journals are all applied psychology journals: *Human Factors*, *Ergonomics*, and *Applied Ergonomics*.

Little guidance appears to be available to authors to indicate which kind of graph to submit. In its recent publication manual, the American Psychological Association (1983, pp. 96-97) gives two specimen graphs. One graph has only two edges. The other graph has four edges, but with calibrations on only two of them. Thus, neither graph is designed to avoid geometric illusions in reading the points. No warning is given in the publication manual of possible geometric illusions.

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