Determinants of the Bourdon effect

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The Bourdon illusion is the apparent inward bending of straight, collinear edges in a solid figure consisting of two elongated triangles meeting at their apexes. This effect was investigated in five experiments. In the first and third experiments, it was shown that the apparent bending is greatest when the apical angles are about 12 deg and the axis of the figure is oriented at about 22 deg from the vertical. The second experiment was a control involving visual acuity for angular departures of two lines from collinearity and served as a basis of selection for subjects in Experiments 3, 4, and 5. Experiments 4 and 5 showed that the illusion occurs strongly in a solid ("filled in") figure but is notably smaller in outline figures of the same size and shape. It tends to be negative in outline figures with boundaries formed by continuous and broken lines. The relationship between the Bourdon illusion and the "negative" Zöllner illusion is considered.

Although the contours AB and BC in Figure 1 are collinear, they appear to be displaced inward toward the points D and E. In consequence, the straight edge, ABC, appears to be bent inward about B. As far as is known, this compelling effect, which was first described by Bourdon in 1902, has not been systematically studied. The five experiments reported here were the first in a series designed to do so.

Two aspects of the Bourdon illusion suggest that it might be different from a number of geometrical illusions of direction. First, the apparent directions of the collinear edges are displaced toward those of their opposite edges, which meet at an obtuse angle. For the most part, illusions of direction are opposed to the direction of the inducing lines or contours. The Zöllner illusion and its numerous derivatives are cases in point. However, there are some notable exceptions in figures in which the angle between inducing and induced contours is about 5 deg (Adam, 1964; Oyama, 1975; Wallace & Crampin, 1969). Under this condition, the test or induced line is apparently displaced toward the inducing line. Thus, one of the issues raised by the illusion in Figure 1 is whether it is essentially the same as these "negative" Zöllner effects. Second, there are scattered references to figures similar in shape to that shown in Figure 1 but consisting of lines only (Luckiesh, 1965; Sanford, 1897; von Kries, cited in von Helmholtz, 1909). Curiously, the illusion reported in these outline figures is opposite to that reported in the solid Bourdon figure; i.e., the collinear line appears to bend *outward* about its center, not inward as in Figure 1. As far as is known, there are no other instances of one direction of illusion in a solid or "filled in" figure and the opposite direction in an outline figure of the same shape. If this opposition between the directions of

the illusion in solid and outline figures of the same shape was confirmed experimentally, an important question concerning the role of contours and lines in the generation of illusions of direction would be posed.

Five experiments are reported. Experiments 1 and 3 were concerned with the effect on the Bourdon illusion of orientation (α) of the figure relative to the vertical and of the inner apical angles (β). (See Figure 3.) Experiment 2 was a control for Experiments 1 and 3, and was concerned with visual acuity for angular departures from collinearity as a function of line orientation. The data from this experiment were also used in the selection of subjects in Experiments 3, 4, and 5. In Experiments 4 and 5, the size and direction of the illusion in solid and outline figures were investigated.

GENERAL PROCEDURE

Subjects

Subjects of both sexes were recruited from among academic staff, research assistants, technical personnel, and graduate students. In pilot studies for Experiments 2 and 3, some subjects exhibited considerable inconsistencies, owing, presumably, to poor motivation or failure to learn the tasks involved. Therefore, subjects in Experiments 3, 4, and 5 were selected on the basis of their performance in the control experiment (Experiment 2), in which the task was that of judging whether lines were collinear. Thus, whereas the number of subjects in Experiments 1, 3, 4, and 5 was predetermined for the particular experiment, that in Experiment 2 accumulated until the maximum was reached with the completion of Experiment 5.

Apparatus

A Data General Eclipse S 200 computer was interfaced with a Tektronix 4014-1 cathode-ray storage-type enhanced module display terminal. The keyboard of the terminal was fitted with a cover with suitable openings that exposed only the four keys to be used. An aluminum viewing tube 20 cm in diameter and 40 cm long, was placed in front of the display, with its axis normal to the screen and at a distance of 5 cm from it. This arrangement resulted in a circular field of view about 22 cm

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in diameter. A rubber mask that fitted the face was fixed at the observer's end of the tube to control distance and to prevent the subject from tilting his head. At the screen, 1 cm subtended a visual angle of 1.273 deg.

The results of each experiment, together with relevant particulars of the subject, were printed up on a second terminal and stored in a file on the computer disk for statistical processing. Processing was carried out automatically by a separate routine.

Stimulus Figures

The basic figure is shown in Figure 1. All figures were light on a dark ground. The luminance of the figures was approximately 14.6 cd/m² and that of the background approximately 3.1 cd/m². The radial distance of each edge from the central apex to the outer end of the figure, which was constant throughout, was 10.5 cm (13.13 deg). All the other figures shown in Figure 2 were derived from that shown in Figure 1.

Procedure

In all experiments, the subject was required to rotate simultaneously two lines or edges in a series of steps in opposite directions until they appeared to be collinear (see Figure 2A). Rotation was achieved by pressing appropriate keys on the console. It was possible to rotate the edges in small steps to the left and upward or to the right and downward in either direction, as shown in Figure 2A. When the subject was satisfied that the

Figure 1. The Bourdon illusion. The edges AB and BC are collinear but appear to bend inward about B toward D and E, respectively.

Figure 2. The stimulus figures used in the five experiments. The symbols α , β , γ_i , and γ refer, respectively, to the orientation of the long axis of the figure relative to the vertical, the internal apical angles of the figure, and the difference between the apparent and physical collinearity in angular terms after an adjustment (the score) and before an adjustment (the starting misalignment).

lines or edges were collinear, other keys were pressed, which generated the next condition.

Both the sequence of conditions and the initial misalignments (γ_i in Figure 2A) were randomized by the computer. At the beginning of the session, each subject was given standard instructions to read and was later invited to ask any questions about the task. Two practice trials were undertaken before the series of experimental trials. The score throughout was the difference in degrees between apparent and true collinearity of the two edges or lines.

EXPERIMENT 1

The purpose of Experiment 1 was to investigate the effect of the angle (α) of the figure relative to the vertical and the size of the internal apical angles (β) on the apparent collinearity of the edges AB and BC, shown in Figure 1. It was expected that, like other illusions of direction, the effect would be greater for oblique orientations of the figure than

for either the vertical or horizontal dispositions (see Day & Dickinson, 1976; Robinson, 1972). Although no predictions were made about the effect of variation in β , it was assumed that if the effect is a manifestation of the negative Zöllner illusion, it would be maximal for an α value of about 5 deg or less, as shown earlier (Adam, 1964; Oyama, 1975; Wallace & Crampin, 1969).

Conditions, Subjects, and Procedure

The stimulus pattern is represented in Figure 2B. There were five values of α —0 (collinear edge vertical), 22.5, 45, 67.5 and 90 deg (collinear edge horizontal)—and three values of β —5, 12.5, and 20 deg. Thus, there were 15 conditions in all. The initial misalignment, γ_i , was randomized within the range of 0 (collinearity) to -3.6 deg. Negative initial values were adopted, since, on the storage-type cathode-ray display used in this experiment, the value of γ could be increased very rapidly by simply adding lines to the top edge of the figure, thus reducing the apparent misalignment. However, to decrease γ , it was necessary to erase the entire figure and redraw it. This latter procedure required at least 20 times as much time as the former. With the negative initial value, the subject could use the fast command mode for most of the trials and the slow negative mode for the relatively rare occasions when there was an overshoot. Since this asymmetry of both γ_i and the control mode is open to criticism, symmetrical values of about 0 and an identical procedure for both positive and negative changes of γ were used in later experiments. It can be noted that no bias due to asymmetry was found in comparing the outcomes of the first and later experiments.

There were eight subjects, each of whom participated twice under each condition, resulting in 30 trials in all. The angular misalignment of the two edges was decreased in steps of .4 deg. The score for each condition was the mean difference in degrees between physical and apparent angular alignment based on the two trials.

Results

Mean angular misalignments (γ) for the five values of α are plotted separately for the three values of β in Figure 3. It can be observed that, as expected, the illusion was greater when the figure was oriented obliquely. It was also notably greater at 22.5 and 45 deg when β was 12.5 deg than when it was at either 5 or 20 deg. These differences among the three values of β were not apparent at orientations of 0, 67.5, and 90 deg. An analysis of variance with repeated measures on the factors α and β showed that the differences between the means for both factors were significant [$F_{\alpha}(2,14) = 13.6, p < .001$; $F_{\beta}(4,28) = 29.0, p < .001$]. The interaction between these two factors was also significant [$F_{\alpha\beta}(8,56) = 3.95, p < .001$].

Two points can be made about these outcomes. First, the Bourdon effect, like the Zöllner and Poggendorff illusions (Robinson, 1972), is greatest when the feature to be judged is obliquely disposed. Second, on first consideration, the occurrence of a significantly greater effect for an internal apical angle of 12.5 deg suggests that the illusion is not a special instance of the negative Zöllner illusion. The negative Zöllner is greatest for angles between

Figure 3. Magnitude of the Bourdon illusion in degrees as a function of orientation (α) of the figure relative to the vertical and the internal apical angles (β) (Experiment 1).

inducing and test lines of about 5 deg and, according to Oyama (1975), is almost negligible at 10 deg. However, the data from Experiments 4 and 5 below have led to a modification of this view. The point is taken up again in the discussion.

EXPERIMENT 2

The purpose of the second experiment was twofold; first, to establish whether variations in the magnitude of the effect as a function of figure orientation is attributable to variations in visual acuity and, second to provide a basis for the selection of subjects for Experiments 3, 4, and 5.

Both the Zöllner and Poggendorff illusions are greater when the property exhibiting illusory distortion is obliquely oriented. It is likely that in each case this is due to poorer visual acuity for both straightness and discontinuity of oblique lines—the oblique effect (Appelle, 1972). In other words, the illusory distortion is greatest when visual resolving power for the relevant object property is poorest. The subject's task in Experiment 1 involved visual acuity for angular departures from collinearity. While this figure has not been traditionally used in the measurement of visual acuity, it is essentially an acuity-based task. It is therefore reasonable to assume that it also exhibits the oblique effect. One purpose of the second experiment was to test this assumption.

As pointed out above, some subjects in pilot studies had exhibited considerable variation in their judgments of collinearity because of obvious difficulties in performing the task. For this reason, performance on the acuity task served as a basis for inclusion in Experiments 3, 4, and 5. The criterion for acceptance was a maximum absolute score of 1.2 deg or less and a mean absolute score of .6 deg or less. Subjects whose maximum or mean score exceeded these values were also excluded from Experiment 2. A total of six subjects were so rejected.

Conditions, Subjects, and Procedure

The stimulus pattern is shown in Figure 2C. Again, there were five values of α : 0 (vertical), 22.5, 45, 67.5, and 90 deg (horizontal). The initial misalignment (γ_i) was randomized over the range ± 1.4 deg in step sizes ($\Delta\gamma$) of .2 deg.

There were 36 subjects, each of whom participated under each condition once. The procedure and scoring were the same as for Experiment 1. The line thickness was .2 mm.

Results

The mean misalignments (γ) for the five α conditions are shown in Figure 4 (lower, broken line). The mean values are small ($\gamma = -.028, -.100, .056, .129$, and $.067$ deg for the α conditions of 0, 22.5, 45, 67.5, and 90 deg, respectively). An analysis of variance indicated that these mean misalignments were not significantly different. However, if the signs are ignored, the absolute values of γ for the same order are .250, .433, .366, .328, and .244 deg (Figure 4; lower continuous line). The trend in the magnitude of these scores is similar to those for the Bourdon effect (Figure 3), with greater errors for the oblique orientations of the figure than for the vertical horizontal. An analysis of variance showed that the difference between these absolute values of γ are significant [$F(4,140) = 4.26, p < .005$]. Further examination by the Newman-Keuls method has shown that only the difference between $\alpha = 22.5$ deg and either $\alpha = 0$ deg or $\alpha = 90$ deg was

Figure 4. Upper: Magnitude of the Bourdon illusion as a function of orientation (α) of the figure relative to the vertical (continuous line: Experiment 3; broken line: Experiment 1). Lower: Apparent collinearity of two lines as a function of orientation relative to the vertical (Experiment 2, continuous line: mean absolute values; broken line: mean values).

significant ($p < .01$). Thus, it can be concluded that, like other visual acuity tasks, the task of detecting angular departures from collinearity exhibits the oblique effect (Appelle, 1972). This can be taken to indicate that the greater Bourdon effects for the oblique orientations of the figure found in Experiment 1 are attributable in some part to poorer visual acuity for alignment when the figure is obliquely disposed.

EXPERIMENT 3

In Experiment 1, the randomized initial misalignments (γ_i) were asymmetrical about zero for the reason pointed out earlier. In addition, an increase in γ was generated faster than a decrease. It is conceivable that these asymmetries of design and adjustment could have affected the outcomes. The third experiment was conducted in order to check on the possibility of bias due to asymmetry in γ_i and speed of adjustment. A total of six subjects were excluded because they failed to satisfy the criteria of acceptance in Experiment 2.

Conditions, Subjects, and Procedure

In order to maintain consistency with Experiment 1, the value of β was 12.5 deg when the leading edges of the figure were in alignment ($\gamma = 0$). For other values of γ , the actual value of β was therefore $12.5 \text{ deg} + (\gamma/2)$. Thus, if $\gamma = 1.4$ deg, the final value of β would be $12.5 + (1.4/2) = 13.2$ deg. There were 25 subjects selected on the basis of a maximum angular acuity score of 1.2 deg and a mean acuity score of .6 deg or less in Experiment 2. The initial alignment was varied over the range ± 2.80 deg with a step size of .4 deg.

Results

To facilitate comparison, mean angular misalignments are shown in Figure 4 (upper continuous line) with those for Experiment 1 (upper broken line). Although the mean for 22.5 deg is slightly less in Experiment 3, the means generally accord well with those of the earlier experiment. The slightly lower score in Experiment 3 at 22.5 deg is probably accounted for by the notably greater scores of two of the eight subjects in the first experiment. The essential similarity between the results indicates that the asymmetrical values of γ_i and adjustment speeds in Experiment 1 did not unduly bias the scores. An analysis of variance showed that, as earlier, the difference between the means was significant [$F(4,96) = 32.5, p < .001$]. Further analysis using Newman-Keuls tests showed that all differences were significant at $p < .01$ level, with the exception of that between $\alpha = 0$ and $\alpha = 67.5$ deg ($p < .05$) and between $\alpha = 22.5$ and $\alpha = 45$ deg (not significant). All these outcomes accord with those for Experiment 1.

EXPERIMENTS 4 AND 5

The Bourdon illusion was originally observed in a solid figure like that shown in Figure 1. In outline

figures of the same shape, the illusion is claimed to be in the direction opposite to that in Figure 1. That is, the collinear lines opposite to those forming an obtuse angle appear to bend outward at about the center point. However, while this direction of the effect has been reported from time to time (Luckiesh, 1965; Sanford, 1897; von Kries, cited in von Helmholtz, 1909), it has not been shown experimentally. The main purpose of Experiment 4 was to compare the direction and magnitude of the illusion in solid and outline figures. The scope of the experiment was extended by constructing the outline figures of continuous and broken (dashed) lines. While the inclusion of these two types of lines was mainly exploratory, it was thought that the broken test lines might be more conducive to the illusion than continuous lines. In the interests of a complete design, four combinations of continuous and broken lines were included as shown in Figures 2E and 2F.

Since the effect with line figures was small, Experiment 5 was conducted to establish whether or not this was due to the absence of enclosing arcs at the ends of the figures (see Figure 5). Apart from this slight difference, the procedures for Experiments 4 and 5 were essentially the same. For this reason, the two experiments are described together.

Conditions, Subjects, and Procedure

The stimulus figures are shown in Figure 2E and 2F. In Experiment 4, there were five figures—the solid figure and four line-figures with open ends. Of these, one consisted of continuous

lines, one of broken (dashed) lines, and the remaining two of continuous and broken lines along one or the other contour. Each broken line consisted of 60 elements, .8 mm long. All lines were again .2 mm thick. The figures in Experiment 5 were the same, except that the ends were completed by arcs of the same radius as those forming the ends of the solid figure. For all figures, α was 22.5 deg and β was 12.5 deg, the combination that produced the greatest effect in Experiment 1.

The criterion for the selection of subjects was the same as for Experiment 3. There were 14 subjects in Experiment 4, and 7 in Experiment 5. The procedures for presentation of the figures and for arriving at the scores were the same as before.

Results

The mean scores for the two experiments are shown in Figure 5. It can be seen that the graphs for the two experiments are similar, suggesting that neither the relatively small effects with outline figures nor the negative directions for two conditions in Experiment 4 are attributable to the absence of enclosing endlines. In both experiments, the illusion was notably greater for the solid figure. The illusions in the outline figures was slightly negative in both experiments when one of the bounding lines was continuous and the other broken.

An analysis of variance of the data for Experiment 4 showed that the difference between the means was significant [$F(4,52) = 30.2, p < .001$]. Further analysis using the Newman-Keuls procedure indicated that the difference between the illusion with the solid figure (Condition 1) and each of the other conditions (2-4) were significant at $p < .01$. Those between Condition 5 and Conditions 3 and 4 (the negative effects) were also significant, both at $p < .01$. None of the other differences achieved significance. An analysis of variance for Experiment 5 also showed that the difference between the means was significant [$F(4,24) = 16.0, p < .001$]. Since the data for this experiment were strikingly similar to those of Experiment 4, a detailed analysis was not considered necessary.

DISCUSSION

In summary, the Bourdon illusion of direction is markedly greater in a solid figure than it is in an outline figure of the same shape and, in the former, achieves a maximum of about 3.0 deg when the internal apical angles are about 12.5 deg and the axis of the figure is inclined at about 22.5 deg to the vertical (Figures 3 and 4). When the figure is vertical or horizontal, the effect is not only much reduced but is also about the same in magnitude for internal acute angles between 5 and 20 deg. Finally, the illusion exhibits a tendency to reverse its direction, i.e., the collinear lines appear to bend outward when one long boundary is a continuous line and the other, opposite to it, is broken or dashed.

Among the most intriguing outcomes of these experiments are the relatively large illusion of direction in the solid figure, the figure in which this illusion was

Figure 5. Magnitude of the Bourdon illusion for a solid figure and for figures formed by lines (Experiments 4 and 5).

originally but briefly mentioned by Bourdon (1902), and the slight effects with various forms of outline figure. As far as is known, this is the only instance so far described of a greater illusion in a solid figure. The observation raises the question of whether other "assimilative" illusions that are commonly associated with outline figures are greater when the figure is solid. The finding suggests that contours between extended regions of light and dark might interact in a manner different from that of mere lines in generating some illusory distortions.

Contrary to earlier reports (Luckiesh, 1965; Sanford, 1897; von Kries, cited in von Helmholtz, 1909), the illusion in the outline figure with continuous lines forming the boundaries is not negative; i.e., the collinear lines do not appear to bend outward, away from the figure. The illusion is in the same direction as in the solid figure, but markedly smaller. However, the illusion is reversed but remains slight when one of the long boundaries is formed by a continuous line and the other by a broken line. This occurs irrespective of which boundary is continuous and which is broken. At this stage, the basis of the reversal is unclear. Clearly, a more detailed investigation of the effect of different classes of lines in various combinations is called for.

Another issue to be considered is whether the Bourdon illusion is an instance of the "negative" Zöllner illusion, the slight apparent tilt of a line in the same direction as another that meets it at a small angle. On first consideration, the two seem unrelated. The data from Experiments 1 and 3 show that the Bourdon effect is greatest when the angle between the two edges is about 12.5 deg. When the angle is 5 deg, the illusion at 22.5 deg from the vertical is much less. Adam (1964) showed that the negative Zöllner illusion is maximal when the angle between the two lines is 2 deg, and Oyama (1975) showed that when this angle is 10 deg, the illusion is negligible. However, it is to be noted that all experiments so far on the negative Zöllner illusion have been conducted with figures in which the long test lines are vertical. As can be seen in Figures 3 and 4, the Bourdon illusion is very slight

when the collinear edges are vertical. In addition, there is no difference in the illusion when the three internal angles vary between 5 and 20 deg for a vertical figure (Figure 3). Thus, while at first the Bourdon and negative Zöllner illusions seem to be different effects, closer consideration does not wholly support this view.

Finally, it is to be noted that the greater Bourdon illusion for obliquely oriented figures is characteristic of most illusions of direction and alignment. Both the Zöllner and Poggendorff illusions are greater when the figures are obliquely disposed (Robinson, 1972). Most forms of visual acuity deteriorate when the test elements are oblique (Appelle, 1972). The discrimination of angular departures from alignment is an acuity task, although it has not been commonly used as such. It is likewise poor when the two lines to be judged for their collinearity are oblique. It can be concluded, therefore, that the greater Bourdon effect for the oblique orientation of the figure (Figure 1) is attributable in large part to poorer visual acuity with oblique contours.

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