The Bourdon illusion occurs with straight-, right-angle-, and parallel-edge figures

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The Bourdon illusion is the apparent bentness of the straight edge of a figure consisting of two elongated triangular components arranged apex to apex. In three experiments, the illusion was shown to occur in the opposite direction, with the components arranged base to base. It was also shown to occur with the component edges at right angles and parallel. With the edges at right angles, the illusion also occurred in one direction when the components were apex to apex and occurred in the opposite direction when they were base to base. Supplementary observations indicated that the illusion is stronger when the components are relatively small and widely separated and eliminated when one of the two edges is curved.

The Bourdon illusion can be seen in Figure 1; the perfectly straight edge, AC, appears to be bent about its center, B, in the same direction as the opposite edge, DBE. This illusion was originally described by Bourdon (1902) in a horizontal version of Figure 1. In the first systematic investigation of the effect, Rozvany and Day (1980) found it to be relatively strong in solid (i.e., "filled-in") figures such as Bourdon's (1902) original figure but weak, negligible, or even slightly negative in outline figures. They also found that the illusion was maximal when the central angles were about 12.5° and the whole figure tilted with the straight edge at about 22.5° , as in Figure 1.

The Bourdon illusion has been investigated in greater detail by Walker and Shank (1987, 1988a, 1988b) and Wenderoth and O'Connor (1986, 1987a, 1987b). The former showed that it occurs more strongly when the figure is delineated by illusory contours and that the bent edge of the figure (DBE in Figure 1) appears to be straighter than it is. Thus, there are two illusions in the Bourdon figure: the straight edge appears to be slightly bent and the bent edge appears slightly unbent. Walker and Shank (1988a, 1988b) went on to show that, in Bourdon figures delineated by both real and subjective edges, the former induced apparent bending in the latter but not vice versa. In the first of three papers, Wenderoth and O'Connor (1986) reported that the apparent inward displacement of edges occurs also in a single triangular component of a two-component figure, such as that in Figure 1. They later showed (Wenderoth & O'Connor, 1987a, 1987b) that the illusion occurs only when the straight edge is tilted relative to the vertical, that it is en-

Figure 1. The Bourdon illusion. The straight edge, AC, appears to be bent inward about B.

hanced when there is a small gap between the apexes of the two components at the center of the figure, and that it is reduced when the apexes overlap to form a "thick neck."

Wenderoth and O'Connor's (1986) finding that edges are displaced inward in single triangular components (i.e., an apparent reduction in the apical angle) suggests that the apparent bending of the straight edge of the complete figure is one of a number of effects the direction and form of which will depend on the way in which the two components of the figure are arranged. For example, it

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can be expected that if the components are arranged with their bases, rather than their apexes, contiguous (as in Figure 2B), the direction of apparent bending along the straight edge will be reversed. It can also be expected that if the two components are arranged with edges AB and DC (see Figure 1) at right angles, illusions of angle size will occur. If the apexes are contiguous, the right angle formed by the outer edges should appear to be acute (see Figure 2C); if the bases are contiguous, this right angle should appear to be obtuse (see Figure 2D). Likewise, with the components arranged side by side with the same two edges parallel, the latter would be expected to appear divergent at their apical ends (see Figures 2E and 2F).

The primary purpose of the three experiments described here was to test these expectations. There were several worthwhile reasons for doing so. First, the occurrence of reversed, angular, and parallelness versions of the Bourdon illusion would not only extend the range of this group of illusions but would confirm Wenderoth and O'Connor's (1986) finding that the basic effect is apparent inward displacement of edges in single components of the figure. Second, it cannot be assumed that the occurrence of an illusion involving one stimulus dimension, such as edge orientation, will necessarily extend to other parameters, such as right angularity and parallelness. When Müller-Lyer figures are arranged one above the other with the apexes of the terminal angles vertically aligned, the latter appear misaligned in the opposite direction to that predicted from the Müller-Lyer illusion, an effect referred to as the *Morinaga paradox* (Day, Bellamy, & Norman, 1983; Morinaga & Ikeda, 1965). There are numerous other instances of nontransfer of an illusion to other stimulus dimensions (see Day & Parks, 1989). It is therefore of interest to establish whether the Bourdon illusion is confined to straight edges (as in Figure 1) or whether it transfers to right-angle and parallel edges, thus producing illusions of acute and obtuse angles and divergence.

In the first of our three experiments, the components of the Bourdon figure were arranged either apex to apex (as in Figure 1) or base to base. The task of the subjects was to adjust edges AB and BC to apparent straightness. In the second experiment, the components were again arranged apex to apex or base to base, but the task was to adjust the outer edges to an apparent right angle. For the last experiment, the components were placed side by side and the task was to adjust the two outer edges to appear parallel. Some informal observations with small, widely separated components are also reported.

EXPERIMENT 1

Wenderoth and O'Connor (1986) measured the apparent bentness of the straight edge in the Bourdon figure by requiring subjects to adjust two lines pivoting about their inner ends to appear parallel to the two component edges. That is, the two lines were rotated to form an obtuse angle, with each arm parallel to an edge. They also showed, by means of this parallel-matching procedure, that the illusion occurs in the same direction when the task

is to adjust one line to appear parallel to the edge of a single triangular component of the figure. This outcome indicated that the conventional Bourdon illusion is a compound of two edge-orientation effects, one in each of the two components, leading to an apparent contraction of the apical angles. Thus, it can be expected that, with the components placed base to base, the illusion will be evident but in the reverse direction (i.e., with the straight edge of the figure apparently bent inward at its center rather than outward as in Figure 1). Our purpose in Experiment 1 was to establish whether this is so by comparing the size and direction of the illusion in the conventional apex-to-apex arrangement with those in the base-to-base arrangement. For convenience, these arrangements are occasionally referred to as the *standard* and *reverse* figures.

Method

Subjects. There were 12 subjects (6 women and 6 men), recruited from among undergraduates, graduate students, research assistants, and technical staff.

Apparatus. The apparatus included a TV monitor, a computer, a mouse for adjusting the figure on the monitor screen, and a chinrest for controlling viewing distance. The screen of the monitor was masked except for a central circular region 17 cm in diameter. The figures were presented at about the center of this region. A blue gelatin filter sandwiched between the screen and the mask and extending over the circular region reduced the luminance of the figures to the comfortable level of 2 cd/m². The figures were blue-green in color and were clearly etched in a dark field. The computer was programmed to generate the stimulus figures, present them in alternating order, vary the starting position for the adjustments of the edges to apparent straightness, and score the angular difference between true and apparent straightness in degrees. Adjustment of the two component edges to apparent straightness was achieved by moving the mouse toward and away from the screen. Movement toward the screen rotated the two components in the direction of an acute angle between the test edges; movement away rotated them in the direction of an obtuse angle. When pressed, a key on the mouse brought on the next figure and saved the last position of the current figure as the response. The viewing distance was 114 cm, so that 1 cm at the screen subtended a visual angle of 0.5° viewing distance. The position of the eyes on the same level as the center of the screen was maintained by a height-adjustable chinrest.

Stimulus figures. The standard and reverse figures are shown in Figures 2A and 2B, respectively. There was an 8-mm gap between the two components in both figures, since Wenderoth and O'Connor (1987b) showed that a small gap between the apexes of the standard figure enhances the illusion. In addition, the base edges formed an acute angle with the test edges so that the components of the reverse figure could rotate without overlapping. There is no reason to suppose that the latter modification affected the size of the illusion. The test edges of each component were 65 mm long, the opposite edges were 58.5 mm long, and the base edges were 16.5 mm long. The apical angles were 14°, and the base angles were 60° and 106°. When the test edges together formed a straight edge (i.e., when they were aligned), the edge was tilted at 22.5° to the vertical.

Procedure. The subjects were required to rotate (using the mouse) the two components so that the test edges appeared aligned to form a straight edge with a gap at the center. Movement of the edges was in repeated steps of 0.5°. The subjects were instructed with the help of diagrams. It was emphasized that the edge of the figure should appear straight. There were no restrictions on the time taken to make the adjustments. On the completion of an adjustment, the subject pressed the key on the mouse to bring up the next figure. Figures 2A and 2B were presented four times each in alternating order. For

Figure 2. Straight-edge (A and B), right-angle-edge (C and D), and parallel-edge (E and F) figures used in Experiments 1, 2, and 3, respectively.

each presentation, the test edges were bent between 5° and 10° about the center of the figure and the direction of initial bentness was also alternated. The score was always the mean difference in degrees between physical straightness (i.e., 180°) and apparent straightness (i.e., the angle to which the edges were adjusted). Scores in the direction to compensate for the illusion in Figure 1 were treated as positive and those in the opposite direction were treated as negative. It was therefore expected that the scores for Figure 2A would be positive and those for Figure 2B would be negative.

Results and Discussion

The mean scores and their standard deviations are shown for the two figures in Table 1. The mean for Figure 2A was positive and that for Figure 2B was negative, with the former greater in absolute terms than the latter. All 12 scores for the standard figures were positive, and all 12 for the reverse figure were negative. In addition, the score for the standard figure was always greater than that for the reverse figure. Both means were significantly greater than zero [for standard figures, $t(11) = 11.41$, $p < .001$; for reverse figures, $t(11) = 6.08$, $p < .001$] and were significantly different from each other [$t(11) = 9.24$, $p < .001$]. The difference between the two means was also significant when the signs were ignored [$t(11) = 5.21$, $p < .01$]. That is, the absolute difference between the means for the standard and reverse figures was significant.

The main finding from this experiment is that the Bourdon illusion is not limited to the apex-to-apex figure but occurs, as predicted, in the opposite direction when the components are reversed so that they are base to base. However, the size of the illusion in the reverse figure is smaller than that in the standard figure. Since this difference occurred also with right-angle figures (see Experiment 2 below) and in the haptic mode with three-dimensional stimulus objects (Day, 1990), it is considered in general terms in the final discussion below.

EXPERIMENT 2

Since the Bourdon illusion is evident as an edge-orientation effect in a single component of the conventional figure (Wenderoth & O'Connor, 1986) and as a bent-edge effect in either direction in the standard and reverse figures (Experiment 1), the question arises as to whether it will also be evident as an angle effect with the same two edges forming a right angle. More specifically, will the right angle appear acute when the components are apex to apex and appear obtuse when they are base to base, as would be expected from the direction of apparent bending of the straight edge in Experiment 1? The purpose of Experiment 2 was to answer this question.

Method

Subjects. There were again 12 subjects (6 women and 6 men), recruited from the same groups as before.

Apparatus. With the exception of a keyboard to replace the mouse, the apparatus and experimental conditions were the same as before. Informal observations made after the completion of Experiment 1 showed that rotation of the components by keypressing was strongly preferred to that by movement of the mouse. The basis of this preference was that coarse adjustments (repeated 0.5° steps) could be made by holding down the keys and fine (0.5°) adjustments could be made by pressing them repetitively. One key rotated the test edges in one direction and the other in the opposite direction. A third key brought up the next figure in the alternating stimulus sequence.

Stimulus figures. The two figures are shown in Figures 2C and 2D. The dimensions and angles of the components were the same as before. The components were arranged so that when their outer test edges were at right angles, each was at 45° to the vertical. The reason for this arrangement was that, had one edge been at 22.5° (as in Experiment 1), the other would have been at 67.5° in order

Table 1
Mean Scores and Standard Deviations for the Three Experiments Involving the Stimulus Figures Shown in Figure 1

Stimulus Figure	<i>M</i>	<i>SD</i>
Experiment 1		
A	2.96	0.90
B	-1.83	1.04
Experiment 2		
C	6.15	6.59
D	-3.06	5.80
Experiment 3		
E	3.91	2.50
F	5.11	2.90

to form a right angle. At the latter angle, the Bourdon illusion in the standard figure is very slight or negligible (Rozvany & Day, 1980). At 45°, it is large and positive. Therefore, to maximize the effect, both edges were at 45°, at which they formed a right angle.

Procedure. The subjects were again required to rotate the components either by holding down or repeatedly pressing the two keys so that the two outer edges appeared to be at right angles. The figures were presented in alternating order four times each. The starting angles for each trial were again always between 5° and 10° greater or smaller than a right angle, and their direction again alternated from trial to trial. The score was the mean difference in degrees between apparent and true right angularity, with those scores in the direction to compensate for the illusion in Figure 2C scored as positive and those in the opposite direction scored as negative. Since the components in Figure 2D were reversed relative to those in Figure 2C, it was expected that the scores would be positive in the former and negative in the latter. In other words, it was expected that the outer edges of Figure 2C would be adjusted to an obtuse angle (positive) and those of Figure 2D to an acute angle (negative).

Results and Discussion

The mean scores and their standard deviations are shown in Table 1. It can be seen that the mean for Figure 2C was positive and that for Figure 2D was negative and smaller in absolute terms. Both means proved to be significantly greater than zero [for Figure 2C, $t(11) = 20.50, p < .001$; for Figure 2D, $t(11) = 1.83, p < .05$] and significantly different from each other [$t(11) = 5.24, p < .001$].

These outcomes leave no doubt that the Bourdon illusion occurs when the components of the figure are arranged with their test edges at right angles. As with the straight-edge figures in Experiment 1, the illusion was greater with the two components apex to apex than when they were base to base. It can also be noted that the illusion with right-angle figures was larger than that with straight-edge figures. The differences in the size of the illusion between the two arrangements of the components and between straight-edge and right-angle-edge figures are discussed below (see General Discussion).

EXPERIMENT 3

The occurrence of the Bourdon effect in single components of the standard figure also leads to the expectation that an illusion of nonparallelness will occur when the two components are placed side by side with edges AB and BC in Figure 1 parallel. The data from Experiments 1 and 2 predict that the two edges will appear to diverge toward the apexes of the components. Our concern in Experiment 3 was with testing this prediction.

Method

Subjects. There were again 12 subjects (7 women and 5 men) from among the same groups as those in the two earlier experiments.

Apparatus and stimulus figures. The apparatus and experimental conditions were the same as for Experiment 2. The stimulus figures are shown in Figures 2E and 2F. The linear and angular dimensions of the components were also the same as before. When the edges were parallel, they were oriented at 45° to the vertical, an angle at which illusory effects are usually at a maximum due to interaction with the oblique effect (see Day & Dickinson, 1976).

The two components rotated together about the centers of their inner edges when the appropriate keys were held down or tapped. When one of these keys was used, the components rotated in the direction of divergence at their apical ends; when the other key was used, they rotated in the direction of convergence. A third key brought up the next figure in the alternating sequence.

Procedure. The subjects' task was to rotate the two components by means of the keys so that the outer edges of the figures appeared to be parallel. The starting position before each adjustment was between 5° and 10° divergence or convergence of the edges at the apical end of the figures. The two figures were presented four times each in alternating order; for each figure, the divergent and convergent starting positions also alternated. The score was the mean difference in degrees between true parallelness of the edges treated as zero and the angle of divergence or convergence for apparent parallelness. It was expected that the edges would be adjusted to convergence toward the apical ends of the components for apparent parallelness (i.e., to compensate for the apparent divergence of the edges when parallel). This direction of adjustment was therefore scored as positive and the opposite direction as negative.

Results and Discussion

The mean scores and their standard deviations are shown in Table 1. It can be seen that the means for both figures were positive, with that for Figure 2F greater than that for Figure 2E. Three t tests showed that both means were significantly different from zero [for Figure 2E, $t(11) = 5.53, p < .001$; for Figure 2F, $t(11) = 6.08, p < .001$] and significantly different from each other [$t(11) = 4.30, p < .01$].

These data clearly confirm the occurrence of the Bourdon illusion when the two components are side by side with their outer edges parallel. A secondary outcome of Experiment 3 is the greater apparent divergence in the right-tilted figure (Figure 2F) than in the left-tilted figure (Figure 2E). This is probably due to an interaction between the Bourdon illusion and an anisotropy of apparent parallelness between right- and left-tilted parallels reported by Rochlin (1955). Rochlin showed that when two thin lines in a homogeneous field are adjusted so that they appear exactly parallel, there are small constant errors relative to true parallelness. The error for right-tilted lines is greater than that for left-tilted lines. As with most visual spatial anisotropies, there is no explanation for this difference. Here, it is sufficient to note that an anisotropy of parallelness occurs and varies with orientation. It can be assumed that this effect of unknown origin interacted with the Bourdon illusion in the parallel-edge arrangement of the components.

GENERAL DISCUSSION

The results of the three experiments are consistent with Wenderoth and O'Connor's (1986) finding that the basis of the Bourdon illusion is an apparent inward displacement of the edges of the triangular components that together form the conventional figure. The apparent bending of the aligned edges in Figures 2A and 2B, the apparent obtuse angle and acute angle in Figures 2C and 2D, respectively, and the apparent nonparallelness of the outer edges in Figures 2E and 2F can be regarded as

compounds of the basic edge-displacement effect in each component. In this sense, the Bourdon illusion can be said to extend to the spatial dimensions of straightness, angularity, and parallelness. In other words, the effect in the conventional figure is one of a range of illusions that is a compound of the edge-displacement effect that reduces the apparent size of the apical angle.

Two issues from these experiments warrant further discussion: (1) the fact that there is consistently greater illusion with apex-to-apex figures than with base-to-base figures, and (2) the variation in the size of the illusion according to whether the edges are aligned, at right angles, or parallel.

Intuitively, the Bourdon figure might seem more likely to appear to bend about the narrow center formed by the apexes than the broad center formed by the bases. That is, a figure or object that is narrower at the center than at its ends would seem, on the face of it, more "bendable" than if the reverse obtains. However, the gap at the center in Figure 2B seems just as readily to "allow" bending, as does that in Figure 2D. In these terms, it is unlikely that the difference in the size of the illusion between the two figures is due simply to a difference in apparent potential or "affordance" for bending. Nor can the difference be readily accounted for by more salient cues for either straightness or right angularity in apex-to-apex figures. In short, the basis of this difference is, for the time being, unclear. Incidentally, it can be noted that the difference is also clearly evident in haptic perception when the fingers are moved across the opposite surfaces of an object with the same frontal profile as Figure 1 (Day, 1990).

The means for the straight-edge figures (Figures 2A and 2B) in Experiment 1 were 2.96° and -1.83° , respectively; the means for the right-angle figures (Figures 2C and 2D) in Experiment 2 were 6.15° and -3.06° , respectively. Although these two pairs of means derived from different experiments, it is reasonable to suppose that, since the subjects were from the same sources and the same methods were used, the difference between them would be sustained in the context of a single experiment. A likely basis for the difference is better discrimination of straightness (i.e., alignment of edges) than of right-angularity. If ability to discriminate straightness is better, it is reasonable to expect that the process associated with the illusion will exercise a weaker effect. This argument is essentially the same as that concerning differential intrusion of the illusion process when discrimination varies with stimulus orientation—the oblique effect (see Day & Dickinson, 1976).

If the strength of an illusion is inversely related to discriminative capacity (i.e., acuity) for a particular stimulus property, such as straightness, it follows that if the stimulus arrangements are such as to reduce acuity, the illusion will be increased. This point has been clearly made by Wenderoth and O'Connor (1987b) in their discussion of the reduced illusion in outline figures. That the point is valid is suggested by Figures 3A, 3B, and

Figure 3. The Bourdon illusion with small, widely separated components. In A, B, and C, the aligned edges appear to be misaligned. In D, the aligned edges appear aligned but slightly curved at their outer ends (see text).

3C, in which the stimulus components are widely separated, an arrangement that adversely affects alignment acuity (Sullivan, Oatley, & Sutherland, 1972). Although no measurements have yet been made with these particular figures, it seems that the illusion is notably greater than that in the more conventional figures with long, narrowly separated components. This is especially so for the base-to-base figures. Apparent bending of the straight edge is slight, in Figure 2B, whereas it is clearly evident in Experiment 3B. Indeed, the two test edges have the appearance of pointing outward in quite different directions. The point is made even more strongly in Figure 3C, in which the two outline components with short edges are again widely separated. Rozvany and Day (1980) showed that the Bourdon illusion is markedly weaker in outline

Figure 4. A: An illusion attributed by Bourdon (1902) to Lipps. A line through the tangent points on the right of the figure would be straight but appears as if it would be curved in the same direction as that through the tangent points on the left. B: The opposite version of the illusion, with the smaller circle at the center.

figures than in solid figures of the same dimensions. This observation was confirmed by both Walker and Shank (1987) and Wenderoth and O'Connor (1987a). The illusion in Figure 3C is again clearly visible—the two aligned edges apparently point in different directions. This, in turn, suggests that the reduced illusion in outline forms of the standard figure like that in Figure 1 is due to conditions that make for better discrimination of alignment, as was suggested by Wenderoth and O'Connor (1986).

Three further points, all bearing on an explanation of the Bourdon illusion, are worth making. First, in the course of informal observations with well-separated elements (as in Figures 3A, 3B, and 3C), it is clear that there is little or no effect when the lines opposite those forming the straight edge are curved (as in Figure 3D). The two straight edges appear aligned; however, their outer extremities appear slightly curved inward. These observations can be construed as showing either that a straight and a curved line or edge are not confused in the same way as two straight ones or that the feature detectors encoding them do not interact.

Second, it is now established that, along with other illusions in geometrical figures, the Bourdon illusion occurs in haptic space when the components are arranged apex to apex and base to base (as in Figures 2A and 2B). Day (1990) showed that when blindfolded subjects moved thumb and forefinger across the surfaces of objects with the same frontal profiles of the two figures, illusions of bending occurred in the same direction as the visual ef-

fects. This suggests that the illusion may be general and that an explanation entirely in terms of visual processes is incomplete.

Finally, in Bourdon's (1902) original discussion of the illusion in Figure 1, he linked it with that shown in Figure 4A, which he attributed to Lipps. A line drawn on the left of the figure so that it is tangential to all the circles would be curved, and one drawn on the right in the same way would be perfectly straight. However, the latter appears as if it would be curved in the same way as the former. The opposite form of this illusion, which, as far as is known, has not been presented before, is shown in Figure 4B. The straight line formed by the tangent point on the right appears to be curved in the opposite direction to that in Figure 4A. If as Bourdon (1902) suggests these effects, which are in the same directions as those in Figures 2A and 2B, belong in the same class as his original illusion, an averaging process for the direction of an edge is suggested. The tangent points would have to be averaged for the direction (or profile) of an edge to be evident. The point of interest is that these "point-averaged" edges appear to produce the same illusory effects as real edges and, as Walker and Shank (1987, 1988a, 1988b) have shown, as illusory edges. If the perception of a particular edge derives from an averaging of points that delineate it, the illusion described here conceivably arises because points along adjacent edges are included in the averaging process. Such averaging that involves points from adjacent edges could account for the Bourdon illusion in both the visual and the haptic modes and could constitute a basis for confusion or perceptual compromise (see Day, 1989) between them.

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