Dynamic form perception in the bending hourglass: Effects of contrast reversal and visual persistence

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As a white hourglass moves across a black background, the middle appears to lag behind its true position, resulting in the apparent bending of the axis of the hourglass. No such distortion occurs with a black hourglass moving across a white background. The results of two experiments support a visual persistence hypothesis, as opposed to a latency hypothesis.

A slender white hourglass moving horizontally across a black background appears distorted if the observer fixates a stationary point. The center of the white hourglass appears to thicken and to lag behind the top and bottom, an effect that has been called the *bending hourglass* (Walker, 1981). The bending effect disappears if the observer visually tracks the moving hourglass. A black hourglass moving across a white background, however, produces no illusory bending.

Figure 1 shows the black and white hourglasses used in the present study. The stimulus conditions illustrated in this figure are not critical, however. The bending effect is easily produced by moving a white cardboard hourglass at about 30 cm per second across a dark surface at arm's length. The reasons for using the particular displays shown in Figure 1 are explained later.

The present study was designed to assess two possible explanations of the bending effect: a latency hypothesis and a persistence hypothesis. Under the latency hypothesis, the apparent lag of the narrow middle portion of the hourglass is due to its longer reaction time in relation to the wider top and bottom portions. Under the persistence hypothesis, the bending effect is due to the greater visual persistence of the narrow portion of the hourglass. It is also possible that latency and persistence both may be involved in the apparent bending. These hypotheses are discussed in greater detail in later sections.

EXPERIMENT 1

This experiment assessed the effects of light and dark adaptation on the bending hourglass. Since visual persistence decreases with light adaptation and increases with dark adaptation (e.g., Haber & Standing, 1970), the persistence hypothesis predicts greater bending for the white hourglass under dark adaptation, and no bending at all for the black hourglass under either condition of adaptation. The latency hypothesis predicts no differences be-

tween the bending of the black and white hourglasses under the two adaptation conditions. In the Discussion section, we describe these predictions in greater detail.

Method

Subjects. Ten male and 10 female introductory psychology students at the University of Missouri—St. Louis received extra course credit for their participation.

Apparatus and Stimuli. The visual displays were carried by a motor-driven drum 15 cm in diameter and 17 cm tall. The drum was mounted on a tabletop a little below eye level, with its axis vertical, at a viewing distance of 120 cm. The drum rotated 60 rpm clockwise or counterclockwise, providing movement to the left or right, respectively, as seen by the observer.

The hourglasses were 12.7 cm tall, subtending visual angles of 6°, and their sides made angles of 20° with each other. The middle of each hourglass was 3 mm wide, and the top and bottom were 21 mm wide. The hourglasses were mounted on the four displays shown in Figure 1. Each display was 17 cm in height, the height of the drum, and each was wrapped around the drum for viewing by the subjects. Half of each display was white, and the other half was black. Each of the white hourglasses was mounted inside the black area of a display, and occupied a location 3 or 6 cm from the near edge of the black background (see Figures 1A and 1B). The black hourglasses were correspondingly located within the white areas of two of the displays (see Figures 1C and 1D). Thus, the displays containing the black hourglasses represent contrast reversals, or luminance complements, of the displays containing the white hourglasses.

A projector powered by a constant-voltage transformer lighted the white parts of the displays at a luminance of 10 mL and the black parts at 0.28 mL, as measured by a Macbeth illuminometer. A black fixation spot was projected on the center of the rotating display by means of an opaque dot mounted on clear glass in the slide plane of the projector. The spot was clearly visible against the black as well as the white portions of the displays. The room was dark, except for stray light from the projector and light reflected from the display.

In Figures 1A and 1B, each of the solid white areas constitutes an *adapting field*. When the subject fixated the stationary black dot, and when either of these two displays moved from left to right (counterclockwise), the white adapting fields are described as *preceding* the hourglasses. When these displays moved from right to left (clockwise), the white adapting fields are described as *following* the white hourglasses.

In Figures 1C and 1D, the adapting fields are the solid black areas. When these displays moved from left to right, the black adapting

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Figure 1. Hourglass displays in Experiment 1: white hourglasses located (A) 3 cm and (B) 6 cm inside black background, and black hourglasses located (C) 3 cm and (D) 6 cm inside white background.

fields preceded the black hourglasses, and when the displays moved from right to left, the adapting fields followed the hourglasses.

The comparison stimuli (see Figure 2) were the same height as the hourglasses, and were presented lying flat on the tabletop, easily visible in the stray light from the projector. The middle member of the comparison series was straight, and the axes of the other members were bent by successive increments of 10° . The subjects chose the comparison stimulus that most nearly matched the apparent bending of the hourglass, as described in the Procedure section.

Procedure. The experiment utilized a $2 \times 2 \times 2$ factorial design. The factors were location of hourglass (3 or 6 cm from adapting field), color of hourglass (black or white), and temporal order of adapting field (preceding or following). There were independent measures on the location factor and repeated measures on the color and order factors.

Each subject was first shown the stationary hourglass. Two familiarization trials were then given with one display moving to the left and one to the right. The subject was instructed to look at the fixation spot as steadily as possible while viewing the display. The subject's attention was then directed to the comparison stimuli. The subject was instructed to choose the comparison stimulus that most nearly

matched the apparent bending of the hourglass, or to choose a fractional number between the nearest two integer scale values.

Half the subjects viewed the black and white hourglasses located 3 cm inside the black or white background area of the displays (see Figures 1A and 1C), and the other half viewed the hourglasses located 6 cm inside the background area (see Figures 1B and 1D). The sexes were balanced across the location factor. Each subject viewed two of the displays described above, each display moving once to the left and once to the right; thus, each subject made a total of four judgments. Both displays were shown to a subject moving in the same left-right or right-left sequence, and these sequences were counterbalanced across subjects and sexes.

In Figure 1, the adapting fields—the solid black and white areas—are all to the right of the hourglasses. In fact, the left-right positions of the adapting fields were randomly assigned to subjects. For any given subject, the black and white adapting fields were in a constant position, always on the left or the right.

Results

As the white hourglass moved to the left, it was expected to appear bent in the direction of the comparison stimuli on the left side of Figure 2, that is, Stimuli 1L–3L, representing successive 10° increments of bending. Thus, a choice of 1L, 2L, or 3L was given a positive score for the left-moving hourglass, and a choice of 1R, 2R, or 3R was given a negative score. For the hourglass moving to the right, judgments of 1R–3R were positive and of 1L–3L were negative. The observed range of scores was from -1 to $+3$ scale units (-10° to $+30^\circ$). Although the subjects were free to choose fractional scale values, none did.

The scores were converted to degrees of apparent bending. Because the means and standard deviations were correlated, and because there were negative scores, the data were transformed by taking $\log(X + 100)$ before performing an analysis of variance (ANOVA). The factors in the ANOVA were location of hourglass (3 or 6 cm from adapting field), color of hourglass (black or white), and temporal order of adapting field (preceding or following), with repeated measures on the last two factors.

The main effect of color was significant [$F(1,18) = 37.77$, $p < .001$], but the effects of order and location were not [$F(1,18) = 3.98$, $p < .07$, and $F < 1$, respectively]. There was a significant color $\times$ order interaction [$F(1,18) = 7.75$, $p < .02$], but the location $\times$ order

Figure 2. Comparison stimuli in Experiment 1. Axis of hourglass is straight in Comparison 0, and is bent by successive increments of 10° in other members of the series.

and location $\times$ color interactions [$F(1,18) = 1.36$, $p > .25$, and $F < 1$, respectively] and the triple interaction of location $\times$ color $\times$ order [$F(1,18) = 3.45$, $p < .08$] were not significant.

Figure 3 shows the means for all of the experimental conditions. For the white hourglass, all four means differed significantly from zero [values of $t(9)$ ranged from 3.97, $p < .01$, to 8.14, $p < .001$]. For the black hourglass, none of the means differed significantly from zero [no value of $t(9) > 1$].

The nature of the main effects and interactions are readily apparent in Figure 3. The color $\times$ order interaction was due to the greater apparent bending of the white hourglass as the white adapting field followed the hourglass (see Figure 1), since there was no effect of order on the black hourglass. The tendency toward the triple interaction of location $\times$ color $\times$ order was not significant ($p < .08$). Nevertheless, the simple effects of order were tested for the white hourglass at the two levels of the location factor because these simple effects were of interest a priori, based on the persistence hypothesis discussed below. The simple effect of order was significant for the white hourglass located 3 cm from the white adapting field [$F(1,18) = 13.37$, $p < .01$], but not for the 6-cm location ($F < 1$).

Discussion

The latency hypothesis is based on the observation that weaker stimuli typically produce longer latencies, or reaction times, than do stronger stimuli (Johnson, 1923; Raab & Fehrer, 1962; Raab, Fehrer, & Hershenson, 1961; Teichner, 1954). As the image of the moving hourglass sweeps across the retina, the narrow middle portion of the image is lighted more briefly than the wider portions, and thus the middle of the image may stimulate the retina less strongly. Thus, the latency hypothesis is initially appealing—to the extent that the middle of the moving hourglass constitutes a weaker stimulus.

However, there are difficulties with the latency hypothesis. First, consider the duration of the wide and narrow portions of the hourglass in the moving retinal image. The

diameter of the moving display was 15 cm, and its circumference was 47.1 cm, so the display moved at the linear rate of 47.1 cm per second. The middle of the hourglass was 3 mm wide, and the ends were 21 mm wide. Thus, retinal points in the moving image were lighted for 6 msec by the middle of the hourglass and for 45 msec by the widest portions of the top and bottom. For the range of these durations and the level of luminance of the present stimuli, earlier studies have found essentially no relationship between duration and visual reaction times (Raab & Fehrer, 1962; Raab et al., 1961).

A second difficulty with the latency hypothesis relates to the fact that the black hourglass showed no apparent bending. If the apparent bending of the white hourglass were due to the greater latency of the narrow middle portion, then there is no a priori reason why the same consideration should not apply to the black hourglass as well. Thus, there is substantial evidence against the latency hypothesis.

The persistence hypothesis is based on the inverse relationship between the duration of a stimulus and its *visible persistence*, which Coltheart (1980) defined as the continuing visibility of a stimulus for some time after its offset. Coltheart also defined two other varieties of visual persistence: *neural persistence*, activity continuing in the visual system after stimulus offset, and *informational persistence*, continuing availability of information about a stimulus after offset. This last variety of persistence is directly related to stimulus duration and intensity, and provides a basis for iconic memory (see also the review by Long, 1980). Hawkins and Shulman (1979) defined *Type 1 persistence* as a relatively short-term process inversely related to duration and intensity, and *Type 2 persistence* as a longer process directly related to these variables. Thus, the latency hypothesis relies on visible persistence in Coltheart's terms, or Type 1 persistence in Hawkins and Shulman's.

Below a critical duration of about 100 to 300 msec, depending on experimental conditions, shorter stimuli persist for longer periods of time (Bowen, Pola, & Matin, 1974; Efron, 1970; Haber & Standing, 1970). Thus, along the narrower portions of the white hourglass, the trailing edge was expected to lag behind its true position, resulting in the apparent thickening of the narrow portions, and the apparent bending of the axis of the hourglass.

Because visible persistence is inversely related to light adaptation and directly related to dark adaptation, the temporal order of the white adapting field—preceding or following the hourglass—was expected to influence the apparent bending of the white hourglass. In Figure 1A, when the display moved to the right, the white adapting field preceded the hourglass, and when the display moved to the left, the adapting field followed the hourglass. Thus, the subject was more light adapted in the preceding condition, and more dark adapted in the following condition. As expected, there was significantly greater bending for the white hourglass under the following than under the

Figure 3. Results of Experiment 1. Apparent bending as a function of order of adapting field (preceding, following), color (black, white), and location of hourglass (3 cm, 6 cm).

preceding condition, but neither condition produced any significant bending in the black hourglass, also as expected—hence, the color $\times$ order interaction.

The simple effect of the order factor was significant for the white hourglass located 3 cm from the edge of the white adapting field, but not for the hourglass located 6 cm from the edge. Thus, whether the white adapting field precedes or follows makes a greater difference when the hourglass is closer to the edge of the adapting field. These results are also consistent with the persistence hypothesis.

The persistence hypothesis readily accounts for the absence of bending in the black hourglass. As the display in Figure 1C moves to the left, the white background illuminates the retina for 392 msec before the arrival of the top and bottom of the black hourglass and for 411 msec before the arrival of the middle. The arrival of the leading edge of the black hourglass then briefly turns off the retinal illumination. Therefore, the duration of the illumination at all points swept by the black hourglass is well above the critical duration, and thus no differential persistence and no apparent displacement of the leading edge of the hourglass are expected.

As the display in Figure 1C moves to the right, the retinal points are illuminated for 64 msec before the arrival of the top and bottom of the black hourglass, and for 83 msec before the arrival of the middle. Thus, little or no differential persistence was expected for either direction of movement. Indeed, if there were any differential persistence of the lighted portions of the retinal image in this case, then the leading edge of the *wider* portions of the black hourglass should appear to lag behind their true positions, producing apparent bending opposite the effect observed in the white hourglass. In fact, no significant bending of any kind was observed in the black hourglass.

The persistence hypothesis explains the apparent bending of the white hourglass, as well as the absence of bending in the black hourglass, and is consistent with earlier studies showing persistence to be inversely related to the duration of a visual stimulus. On the other hand, the latency hypothesis is inconsistent with earlier failures to observe a relationship between the duration of a stimulus and visual reaction times. Furthermore, the latency hypothesis fails to explain the absence of apparent bending in the black hourglass. Thus, the persistence hypothesis offers greater explanatory power.

EXPERIMENT 2

This experiment was designed to provide further tests of latency and persistence as possible explanations of the bending hourglass. Here, the stimuli consisted of wide and narrow white bars with two of their vertical sides aligned, and two sides nonaligned (see Figure 4).

As a display moved to the left or right, the subject fixated a stationary spot and judged the apparent alignment of the leading and trailing edges of the bars. For example, as the display in Figure 4A moved to the right, if the latency of the narrow bar were greater, then its lead-

Figure 4. Bar displays in Experiment 2: (A) wide bar on bottom, and (B) wide bar on top.

ing edge (the right side of the bar) would appear to lag behind the leading edge of the wide bar; however, if only persistence were at work, then the leading edges of the two bars would continue to appear aligned and their trailing edges would appear less misaligned. As the bars in Figure 4A moved to the left, the longer latency of the narrow bar would increase the apparent misalignment of the leading edges (now the left sides of the bars); however, if only persistence were at work, then the apparent misalignment of the leading edges would neither increase nor decrease, and the trailing edge of the narrow bar would lag behind that of the wide bar.

Method

Subjects. Five male and 5 female introductory psychology students received extra course credit for their participation.

Apparatus and Stimuli. The same apparatus was used as in Experiment 1. The white bars were 6 cm tall, and their ends were 2 cm apart. One of the bars was 3 mm wide and the other was 21 mm wide, the same widths, respectively, as the narrowest and widest portions of the hourglass in Experiment 1. The bars were illuminated as in the previous experiment, the drum rotated at 60 rpm as before, and the same stationary black fixation spot was projected on the displays.

The comparison stimuli are shown in Figure 5. The comparison lines were black, and were 6 cm tall, like the white bars in the moving displays. In the middle member of the comparison series, Comparison 6, the lines were aligned, and in the other members of the series, the lines were misaligned by successive increments of 4 mm. Thus, in Comparisons 1 and 11, the misalignment was 20 mm. Since the objective misalignment of the nonaligned edges in the moving bars was 18 mm, this objective misalignment matched a scale value of 10.5 on the scale of the comparison stimuli.

Procedure. The experimental design was a $2 \times 2 \times 2$ factorial. The factors were alignment of edges (aligned or nonaligned), temporal order of the moving edges (leading or trailing), and configuration of display (wide bar on top or on bottom). There were repeated measures on all three factors.

For control purposes, each subject first viewed a stationary display. The subject was then shown the comparison stimuli and was instructed to choose the comparison stimulus that most nearly

Figure 5. Comparison stimuli in Experiment 2. Bars are aligned in Comparison 6, and are displaced by successive increments of 4 mm in other members of the series.

matched the appearance of the left and right edges of the white bars, or to choose a fractional scale value between the nearest-appearing integer values.

The bars were then shown to each subject in the two configurations in Figures 4A and 4B, once with the wide bar at the top of the display, and once with the wide bar at the bottom. The orders of these configurations were counterbalanced as nearly as possible across the 5 male and 5 female subjects. Each subject viewed each display in the two configurations, moving once to the left and once to the right, and judged the apparent alignment of the leading and trailing edges for each direction of motion, making a total of eight judgments. The orders of movement, left-right and right-left, were individually randomized for each display for each subject, as were the orders of judging the edges, leading-trailing and trailing-leading.

Results and Discussion

In judging the stationary bars, every subject matched the aligned edges with Comparison 6. For the nonaligned edges, the range of matches was from Comparison 9 to Comparison 11, and the mean was 10.6, a value not significantly different from the objective value of 10.5 [$t(9) = .45$]. Each subject's judgments of the aligned and nonaligned edges of the stationary display were used as control measures. For the moving displays, each score was a difference between the judged scale value of the aligned or nonaligned edges and the appropriate control measure.

Under the latency hypothesis, for both the aligned and nonaligned edges, the leading edge of the narrow bar should lag behind its true position with respect to the leading edge of the wide bar, and the trailing edges of the bars should also appear similarly displaced. Under the persistence hypothesis, the trailing edge of the narrow bar should lag behind its true position with respect to the wide bar, but there should be no apparent displacement of the leading edges of the bars. Observed displacements in the expected direction were considered positive, and displacements in the other direction were considered negative. Scores ranged from -3 to +3, representing apparent displacements of -12 to +12 mm.

The scale values were transformed by taking $\log(X+10)$ before performing a repeated-measures ANOVA, in which the factors were edge alignment (aligned or

nonaligned), temporal order of edges (leading or trailing), and configuration (wide bar on top or on bottom). The order effect was highly significant [$F(1,9) = 28.45$, $p < .001$], so the narrow bar was apparently displaced in the expected direction in the trailing edges. The alignment factor produced no significant effect ($F < 1$). The effect of configuration approached significance [$F(1,9) = 3.30$, $p < .11$], so there was a tendency for the bottom configuration to produce slightly greater displacements (1.85 vs. .70 mm). None of the interaction effects approached significance [largest value of $F(1,9) = 1.36$, $p > .27$].

Figure 6 shows the means for the leading and trailing aligned and nonaligned edges. In the leading order, neither the aligned nor the nonaligned edges differed significantly from zero [values of $t(9)$ were -1.41, $p < .20$, and -.90, $p < .40$, respectively]. In the trailing order, the mean for the nonaligned edges was significantly greater than zero [$t(9) = 4.27$, $p < .01$], but the mean for the aligned edges merely approached significance [$t(9) = 1.82$, $p < .11$]. Pooling the effects of order across the levels of alignment, the mean for the leading edges was -.90 mm [$t(9) = -1.30$, $p < .23$] and for the trailing edges was 3.45 mm [$t(9) = 5.86$, $p < .001$].

Under the latency hypothesis, the leading edge of the narrow bar was expected to lag behind the leading edge of the wide bar, but in fact the observed displacement was in the opposite direction, although not statistically significant. On the other hand, the persistence hypothesis predicts no displacement of the leading edges, but does predict the observed displacement of the trailing edges. Thus, the present results clearly support the persistence hypothesis.

GENERAL DISCUSSION

The present results support the persistence hypothesis as an explanation of the bending hourglass in Experiment 1 and of the observed distortions of the moving bars in Experiment 2. Although the operation of persistence

Figure 6. Results of Experiment 2. Apparent displacement of bars as a function of temporal order of edges (leading, trailing) and alignment of edges (aligned, nonaligned).

does not preclude the operation of latency in these effects, neither experiment provides any evidence of differential latency between the wide and narrow portions of the displays. Nevertheless, below *some* width of a narrow bar, latency must surely increase. Under the present conditions, such a critical bar width must lie below a visual angle of 9 min, the visual angle of a 3-mm width viewed at 120 cm.

Visual persistence also produces spatial distortions involving other moving stimuli. For example, a strobe flash on an airplane appears to lag behind its true position if the observer fixates a stationary point near the flight path (Walker & Irion, 1982). In the Pulfrich effect, a neutral-density filter in front of one eye distorts the apparent path of a moving object in depth. The apparent location of the moving object in the filtered eye lags behind its apparent location in the unfiltered eye, producing an apparent displacement in depth in accordance with the geometry of binocular vision. The Pulfrich effect is usually attributed to the greater latency of the image in the filtered eye, although Morgan (1977) attributed the effect to the greater persistence of the dimmer image in the filtered eye, resulting in the widening of that image and the apparent lag of its trailing edge, and its center, in relation to the image in the unfiltered eye.

The results of the present experiments are consistent with earlier observations of the bending hourglass (Walker, 1981) and with related distortions in other moving displays (Walker & Saunders, 1985). If the hourglasses in the present study were laid on their sides, and if the angles between their sides were increased to 45°, the resulting figures would represent black and white bow ties. A white bow tie moving horizontally across a black background develops prominent fins at the top and bottom of the trailing edge if the observer fixates a stationary point, and the trailing half of the figure appears longer than the leading half (Walker & Saunders, 1985). No such distortions occur in a black bow tie moving across a white background.

In many perceptual situations, positive and negative luminance contrast are essentially interchangeable; that is, black stimuli against a white background serve many of the same functions as white stimuli against a black background. For example, in printed text, black letters on

white carry the same information as white letters on black. However, it is very difficult to recognize a familiar face in a photographic negative, or a negative print, even though these displays contain the same information as a conventional positive print (Galper, 1970). The bending hourglass provides another example of strong asymmetry between the effects of black and white stimuli in a perceptual process.

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