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Spatial distortions in rotating radial figures

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Abstract

A white sector on a black rotating disk appears spatially compressed. We found that apparent shrinkage: (1) for sectors ranging from 15 to 150° and rotating at 1.25 rps varied in an inverted U-shaped manner from 3 to 16° and back to 11° (corresponding to 20, 16, and 7.5%, respectively); (2) increased with speed of rotation producing maximal compressions of between 7 and 30° for velocities ranging from 0.8 to 2 rps; and (3) affected the leading and the trailing portions of the rotating sector equally, while allowing for apparent expansion of the middle region. Consistent with these findings we found that (4) two black lines 20 mm apart across the center of the rotating disk and extending outward towards the edge appeared to converge when they were actually parallel and were seen as parallel when their end points were physically diverged by 6°. Our findings suggest a foreshortening process which ensures that the shapes of moving stimuli are perceived approximately correctly, irrespective of whether they are actually sharp or blurred. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Brown–Ansbacher effect; Shape distortion; Apparent compression; Motion foreshortening

1. Introduction

How do we manage to estimate the size and shape of moving objects so well? It is known that the visual system integrates signals over a time period of about 120 ms in photopic vision (Barlow, 1958). Although this temporal summation has the advantage of increasing visual sensitivity, it will greatly blur moving objects. It is also liable to make objects look longer than they really are along the axis of motion. When a bowler swings his arm over his head to deliver a cricket ball, the visual integrating time presumably spreads out the neural trace into something like a bat's wing. Yet this is not what we perceive, whatever our integration time may be, we see not a wing but an arm. We suggest that a perceptual foreshortening process exists which compensates for the elongation of moving objects so that they look about the right thickness.

In support of this idea we study some dynamic phenomena in which moving shapes are subjectively compressed along their motion paths. Burr (1980) found that moving dots looked like motion streaks whose apparent length first increased with exposure duration (30 ms) and then decreased again with further increases in duration (120 ms)—the further the dots traveled, the shorter they appeared. We now report analogous contractions in the perceived width of sectors on a rotating disk, some of our phenomena being closely related to the arc-contraction effects described by Brown in 1937 (unpublished) and Ansbacher (1938, 1944). Using a matching procedure, Ansbacher (1944) found that a thin rotating arc-line (for details see Table 1) illuminated from behind appeared to shrink to only 21% of its actual length. He attributed the apparent shrinkage to 'telescoping' (i.e. uniform shrinkage) and not to a drop-out either of the beginning (leading edge) or the end (trailing edge) of the stimulus. He assumed that visual stimuli are processed in 'active' time periods of constant duration, defined by the Bunsen–Roscoe law of temporal integration [see Barlow (1958), above], that alternate with 'inactive' periods. He termed this alternation 'visual pulsation'.

Using magnitude estimation, Marshall and Stanley (1964) confirmed the apparent shrinkage reported by Brown (1937) and Ansbacher (1944) with a rotating white arc on a black background and, in addition, found a perceived expansion of a black arc on a white

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Table 1

Author(s)	Length of arc/sector (°)	Retinal eccentricity (°)	Speed of rotation (rps)	Luminance of white/black (ft-l)	Contrast (%)	Compression (%)
Brown (1937)	36		1.0	Unknown		'Mere point'
Ansbacher (1944)	22	12	1.3	100[a]	>90	79
Marshall and Stanley (1964)	45	22	1.3	45/3	88	13
Stanley (1966)	8–33	22	1.3	100	>90	65–82
Day (1973)	36 gradient	19	1.0	2.4/<0.5[b] 3.4/0.7[b]	66	16, 51 versus 22
Present study	15–150, 30	4	1.25	7.4/1.1[a]	73	20–7.5, 25 (max)

[a] Estimated.
[b] Converted from cpd/m^2 to ft-l.

background. However, both the shrinkage and lengthening were not very marked. In a further study, Stanley (1966) using a more intense, trans-illuminated arc under otherwise equal conditions, obtained a much larger shrinkage of up to 82% [similar to Ansbacher (1944)]. In comparison, the lengthening of the black arc amounted to only 30%.

A later study by Day (1973) using rotating arcs bearing a luminance gradient showed that apparent contraction is enhanced when a bright, leading portion is followed by a darker, trailing portion. Contraction was 51% with the greater intensity leading as compared to only 22% with the lower intensity leading. For an explanation, he suggested that the retinal neurons become desensitized as a result of rapid light adaptation. He attributed apparent shrinkage to the elevated threshold leading to perceptual disappearance ('visual masking') of the trailing part of the rotating arc. Day also studied the contraction effect as a function of retinal eccentricity and found that shrinkage increased rapidly when the rotating arc was presented at eccentricities $>11°$.

We shall refer to these processes as motion shortening. However, it is only the moving objects, not their motion paths, that appear to be shortened. Moreover, these processes are logically separable from the motion deblurring mechanism which has been proposed by several authors (Burr, 1980; Burr, Ross & Morrone, 1986), but opposed by other authors (Morgan & Benton, 1989; Anderson, Van Essen & Gallant, 1990; Pääkkönen & Morgan, 1994) and by the same authors (Burr & Morgan, 1997). In this paper we describe four experiments in which we analyze the changes in apparent shape and size of sectors and parallel lines that occur when these stimuli are rotated on a disk. These phenomena are summarized in Fig. 1.

The compressed sector effect is illustrated in Fig. 1a and examined as a function of angular size (Experiment 1). This effect is further studied with different rotation velocities (Experiment 2). The relative contributions of the leading versus trailing portions to compression are depicted in Fig. 1b, where a radial line bisecting the sector is perceived as shifted towards the trailing edge (Experiment 3). A related kind of compression is illustrated in Fig. 1c, where two parallel lines appear to converge and curve towards the edge of the disk (Experiment 4).

2. General methods

In all our experiments, an observer fixated the center of a rotating disk driven by a speed controlled motor. The viewing distance was 1.70 m, and the disk diameter was 24 cm (8.0° visual angle). Speed of rotation was 1.25 rps (75 rpm), unless otherwise specified. For a point on the rim of the disk, this value corresponds to a linear velocity of 94.25 cm/s and an angular velocity of 31°/s in the eye of the observer. The luminances of

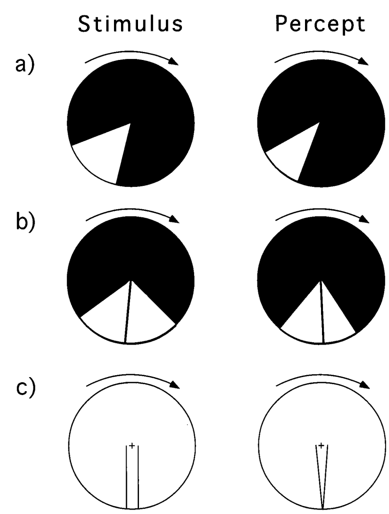

Fig. 1. Rotating stimuli (left column) and what they looked like (right column), drawn not to scale. (a) A rotating sector appeared narrower. (b) When a rotating quadrant was bisected, the leading sector looked wider than the trailing sector. Overall, the whole quadrant appeared compressed. (c) Two lines parallel to the radius appeared to converge and even curve towards each other to touch at the rim of the disk.

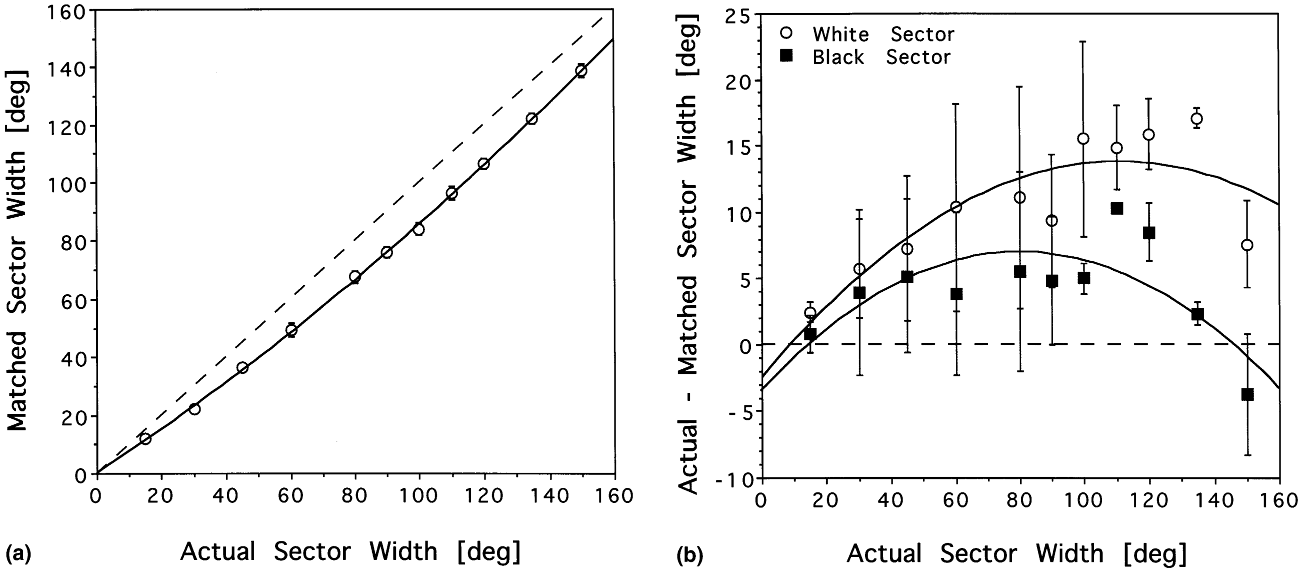

Fig. 2. (a) Matched sector width plotted as a function of actual sector width. Speed of rotation was 1.25 rps. Data points are averages of three matches by each of five observers ($n = 15$). Error bars equal ± 1 S.E., some are too small to be seen. (b) Difference between actual and matched sector width for white sectors on a black background (open circles) and black sectors on a white background (filled squares) as a function of actual sector width. Data points are averages of three matches by each of two observers ($n = 6$). Error bars equal ± 1 S.E.

the black and white parts of the display were 3.9 and 25.4 cd/m^2, respectively, equivalent to a Michelson contrast of 73%. Fixating the center of the disk binocularly, observers estimated the width of a rotating sector, a portion thereof, or the separation of a pair of rotating lines, by setting a hand-held sector or line pair to match the subjective appearance of the rotating stimulus. To ensure an unbiased match, experimental stimuli were always presented in rotation. We found no significant differences between the results for clockwise versus counter-clockwise rotation, so both sets of data were combined. In control experiments, observers estimated the angular size of various static sectors and line pairs three times for each of three different angular positions on the disk. In each of these cases, the matched size agreed almost perfectly with the actual size independently of the tested position.

3. Experiment 1: Compressed sector effect

We first examined the apparent compression of sectors of different widths. The question was whether all sectors were compressed by the same percentage (Weber's Law), or by the same absolute amount (i.e. actual minus apparent length), as Ansbacher (1944) proposed, or by some other function. For this purpose we rotated a black disc at 1.25 rps, bearing a white sector whose angular width was randomly chosen on different trials from the set: 15, 30, 45, 60, 80, 90, 100, 110, 120, 135, and 150°. The observer held in his/her hands a split disk which provided an adjustable white sector on a black disk, of the same dimensions and materials as the rotating stimulus. His/her task was to adjust the size of the hand-held static sector until it matched the apparent width of the rotating sector during fixation of the center of the rotating disk. Observers were told to make their decision carefully without any time constraint. Five observers, four male and one female, were tested. All of them were experienced, aged 30–63 years, and had normal or corrected vision. One was an author (S.A.) and the other four observers were naive to the purpose of the experiment. Each observer made three settings on all conditions. To check for the effect of contrast polarity, the same experiment was repeated for black sectors on a white background using two observers.

3.1. Results and discussion

In Fig. 2a, the apparent width of the rotating sector, as matched by the static hand-held disk, is plotted as a function of the actual sector width. The dashed line represents equality between the two. Data falling below this unit slope line indicate an apparent compression of the rotating sector. They were fitted by a second order polynomial fit. Apparent compression (the difference between the two curves) increases from 3° for the smallest sector (15°) to 16 at 100° sector width, thereafter remaining constant or decreasing slightly. The fitted curve suggests that only for sector widths narrower than 30°, if at all, apparent compression follows Weber's law. This result agrees with the findings of Ansbacher (1944) that after an initial increase of up to

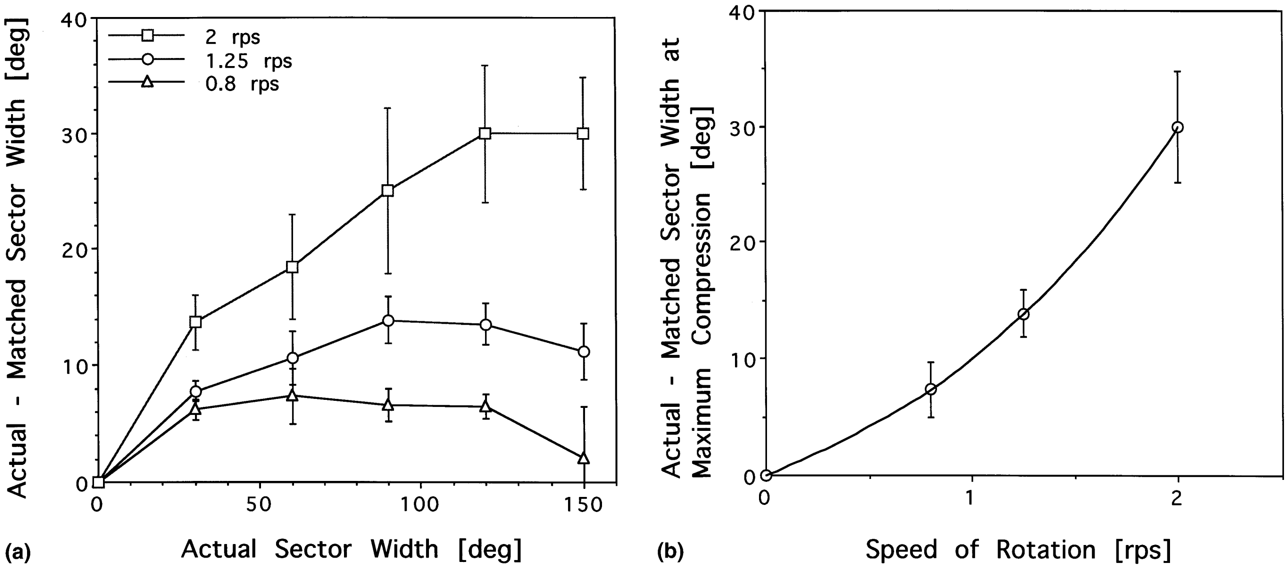

Fig. 3. (a) Difference between actual and matched sector width plotted as a function of actual sector width for three rotation velocities. Results for 1.25 rps were taken from Fig. 2a. Data points are averages of three matches by each of four observers ($n = 12$). Error bars equal ± 1 S.E. (b) Maximum apparent compression (from Fig. 3a) plotted against speed of rotation. Error bars equal ± 1 S.E.

36° arc length, the absolute amount of apparent compression remains approximately constant.

Fig. 2b shows apparent compression defined as the difference between actual and matched width plotted as a function of actual sector width. The upper curve (open circles) refers to white sectors, while the lower curve (filled squares) refers to black sectors. Data are averages from two observers. Both curves have been fitted with a second order polynomial function.

Curves are inversely U-shaped with the maximum compression for white sectors occurring at about 110° and for black sectors at about 80° actual sector width. Compression is stronger for white sectors than for black ones; the difference between the two increases progressively with sector width. At about 145° apparent compression for the black sector changes over to expansion. Both curves if appropriately shifted relative to each other have similar shapes, suggesting similar mechanisms of motion distortion. Our findings for black sectors differ from the observations for black arcs by Marshall and Stanley (1964) who either reported apparent expansion (or no change) in perceived length, whereas we found mostly shrinkage.

4. Experiment 2: Effect of rotation speed on apparent compression

We repeated Experiment 1, using white sectors with widths of 30, 60, 90, 120, and 150°, and rotation velocities of 0.8 and 2 rps. Four of the original observers were tested.

4.1. Results and discussion

Fig. 3a plots the difference between actual and matched sector width as a function of actual sector width for three different velocities. For a rotation speed of 0.8 rps, the curve first ascends, thereafter runs parallel to the abscissa and then descends; similarly, for 1.25 rps (data taken from Experiment 1), the curve first increases and thereafter slightly decreases again at larger sector widths, finally, for a speed of 2.0 rps, the curve increases and then levels off (with the possibility of a subsequent decline). Compared to the two curves from Fig. 2b, the curves in Fig. 3a do not have the same shape.

With increasing speed of rotation, the maximum of each curve is shifted to the right. The peak locations on the abscissa are 60° for 0.8 rps, 90° for 1.25 rps, and 150° for 2.0 rps. Maximum compression (peak values in Fig. 3a) is plotted against speed of rotation in Fig. 3b. The slope of the resulting curve increases with velocity.

These results are consistent with the findings of Ansbacher (1944) that apparent shrinkage increases with increasing speed of rotation. For each peak value at a given speed, we now can compute the duration it takes for that stimulus to travel its own length. For example: at 0.8 rps, a 60° sector requires 208 ms; at 1.25 rps, a 90° sector requires 200 ms; and at 2 rps, a 120° sector requires 166 ms. Given the relative shallow peaks, an average time of 100–400 ms, with a mean value around 200 ms, appears to be realistic. To effectively mask the end of the stimulus and thereby shorten its length (Day, 1973), the leading edge would have to exert an influence onto the trailing edge over that period of time.

5. Experiment 3: Compression of leading versus trailing portions

Do all parts of the rotating sector become equally compressed, or are the leading and trailing portions of the sector more strongly affected than the middle portion in between? We examined this question by presenting a 90° quadrant rotating at 1.25 rps (from Experiment 1) and determining the amounts of compression for various portions within the sector with the aid of a single probe radius.

Mean matches of an undivided 90° quadrant for the five observers serving in this study were: 80° for J.N. and M.S., 76° for S.A. and R.T., and 69° for A.S. These values correspond to overall compressions of 11.1% for J.N. and M.S., 15.6% for S.A. and R.T., and 23.3% for A.S. Mean perceived sector width is 76.2° (15.3%).

Next, a thin, black radial probe line, dividing the white sector into two portions of (usually) different widths, was added to the rotating sector, with its angular position pre-set on each trial by the experimenter. Let us suppose that at first it was set to 45°, bisecting the quadrant. In other words, it was 50% of the angular distance across the rotating sector. Observers held a sector of either 80, 76, or 69° angular width (corresponding to 90° actual sector width) on which was mounted an adjustable radial line, and the task was to set this line to match the apparent angular position of the rotating radius within the presented sector. Suppose that the observer set the matching radius not to 50% of the angular distance across his hand-held sector, but to 55%, making the trailing portion narrower than the leading portion of the hand-held sector. This setting would indicate that compression affected the trailing half more than the leading half. On the next trial the rotating radius might be set to an angular position of (say) 60°, corresponding to 67% actual sector width. Here, the observer might set his matching radius to 75% suggesting that the trailing portion now appeared even more compressed; and so on. This technique was used to trace out the profile of the compression function across the width of the sector.

5.1. Method

The rotating disk contained a white 90° quadrant within which a radial probe was pre-set to 15, 30, 45, 60, or 75°. The stimuli were tested in random order, three times clockwise and three times counter-clockwise. The same five observers as in Experiment 1 participated in this experiment.

5.2. Hypothetical results

The diagram in Fig. 4 illustrates three hypothetical compression functions. The symbols at the top most right corner lie at $x = 90°$, $y = 76.2°$, in agreement with the mean perceived width of a 90° rotating sector (Fig. 2a). In the hypothetical plot given by the filled datum circles, the matched quadrant shown to the left of the graph looks progressively more compressed, with its first quarter (leading edge) looking wide, its second quarter narrower, its third quarter narrower still, and its fourth quarter (trailing edge) narrowest of all. Conversely, the curve with the open circles would occur if the leading portion (# 1) of the sector were more subjectively compressed than the trailing portion (# 4). A straight line plot (open squares) would show uniform compression across the whole perceived sector.

5.3. Results and discussion

In Fig. 5a, matched average probe line settings in percent for five observers were converted to degrees (100% = 76.2°) and plotted as a third order polynomial function of the actual probe positions.

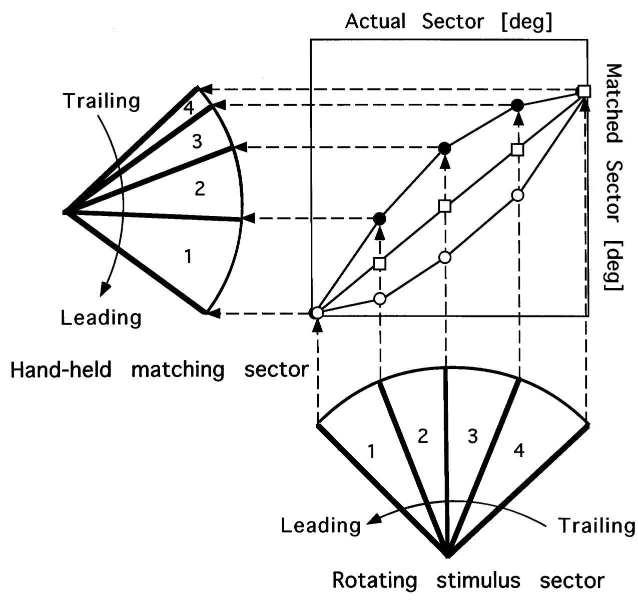

Fig. 4. Three hypothetical compression functions, in which the abscissa shows the actual positions of a radial probe line within a rotating sector and the ordinate its hypothetical perceived angular positions. On the left, the perceived sector looks progressively more compressed (as indicated by the subdivisions), with its first (leading) quarter wide and all subsequent quarters progressively narrower. This increasing compression yields the curve with the filled circles. Conversely, the curve with the open circles would obtain if the leading portion of the sector were to appear more compressed than the trailing portion. A straight line plot with the open squares would show uniform compression across the whole sector. The lower the slope, the greater the compression.

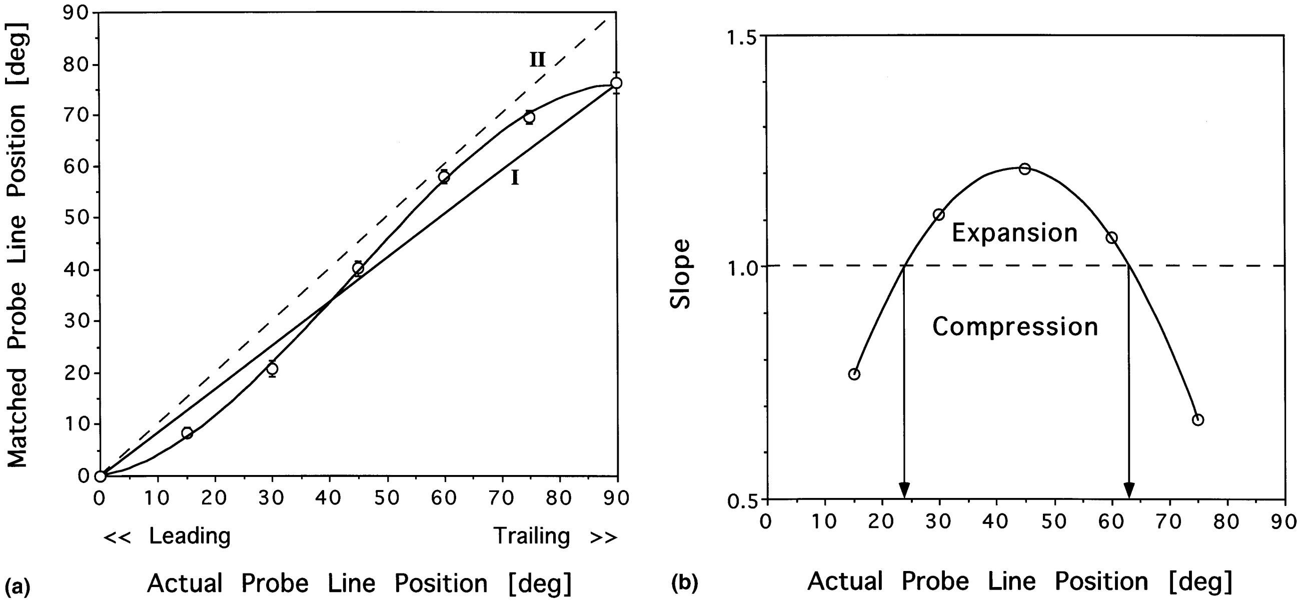

Fig. 5. (a) Matched probe line position plotted as a function of actual probe line position within a 90° white sector rotating at 1.25 rps. 'I' is the connecting line from the origin to mean perceived width (=76.2°) of a 90° rotating sector, 'II' is the unit slope line. Data points are averages of three matches by each of five observers ($n=15$). Error bars equal ± 1 S.E. (b) The derivative (slope) of the curve in Fig. 5a plotted against actual probe line position. The beginning and end of the curve indicate apparent compression ($y<1$), while the central portion between 24 and 63° indicates expansion ($y>1$) with a maximum at 43.5°.

The resulting curve is S-shaped, combining the two outer hypothetical curves in Fig. 4. The curve straddles line I, which connects the origin (0/0) with a value of 76.2° on the right ordinate, i.e. the mean perceived width of a rotating 90° quadrant for all five observers. The curve intersects line I approximately halfway up. In the vicinity of 0 and 90° actual sector width, the slope of the curve is flattest, suggesting that the perceived compression is strongest for both the leading and the trailing portions. (The flatter the curve, the greater the compression). For the middle section the slope of the curve rises above unity, as shown by the dashed line II, indicating that in this region the sector is seen as expanded.

This is brought out more clearly in Fig. 5b, which re-plots the first derivative (=slope) of the curve in Fig. 5a using a second order polynomial fit. The curve illustrates that the transition between apparent compression on one hand and expansion on the other occurs at 24 and 63°, respectively, with the central section subjectively expanded by a factor of 1.21 of its true value at an interpolated probe line position of 43.5°.

Fig. 5a and b show that an apparent shrinkage occurs at both the leading and the trailing ends of the 90° sector. These results differ from the findings of Day (1973) that shrinkage occurs only at the trailing end of the stimulus and that the leading portion of the stimulus masked the trailing portion, thereby reducing both its visibility and its perceived width.

Our findings imply that the perceived compression and expansion, respectively, of a given portion within the total sector remains unchanged irrespective of the position of the probe line. However, this assumption may not hold for more than one divider. For example, when a 90° sector is presented bearing five radial lines dividing it into six 15° subsectors, all our observers perceived the leading portion as the widest and the trailing portion as the narrowest one. This is different from what would be expected on the basis of Fig. 5a. Even when only two radial lines were used to divide the 90° sector into three 30° portions, the first portion was again perceived as the widest and the last as the narrowest.

6. Experiment 4: Non-parallel line effect

The finding that a rotating sector appears compressed led us to try a different pattern, namely, two thin black parallel lines drawn from the center to the edge of a circular disk. When spun, the two lines no longer looked parallel, but appeared to converge and even curved toward the edge of the circle (Fig. 1c).

We measured this 'non-parallel effect' by a matching method of adjustment, similar to the one used in Experiment 3. On different trials the lines were either parallel, converging or diverging toward the periphery of the circle, and we collected settings of the lines' appearance in every case. The two lines had a length of 12 cm and were always 20 mm apart across the center of rotation of the disk, whilst their separations at the edge of the circle were set on different trials to values of 5, 10 and 15 mm (lines converging toward the edge), 20 mm (parallel lines), or 25, 30, 35, 40, 45, 50, 55 and 57.5 mm apart (diverging lines). The disk had a diameter of 24 cm and rotated clockwise at 1.25 rps as before; viewing distance was again 1.70 m.

The observer held in his/her hands a white disk provided with two adjustable black lines, similar in appearance to the rotating stimulus. One line was printed on a white card disk, and the other line was printed on a transparency which pivoted on a pin that pierced the center of the cardboard disk. The observer's task was to adjust the separation between the lines on the hand-held disk until it best matched the appearance of the pair of rotating lines. As in the previous experiments, observers fixated the center of the rotating disk while making judgements. Four observers were tested and each of them made three settings in random order on all conditions.

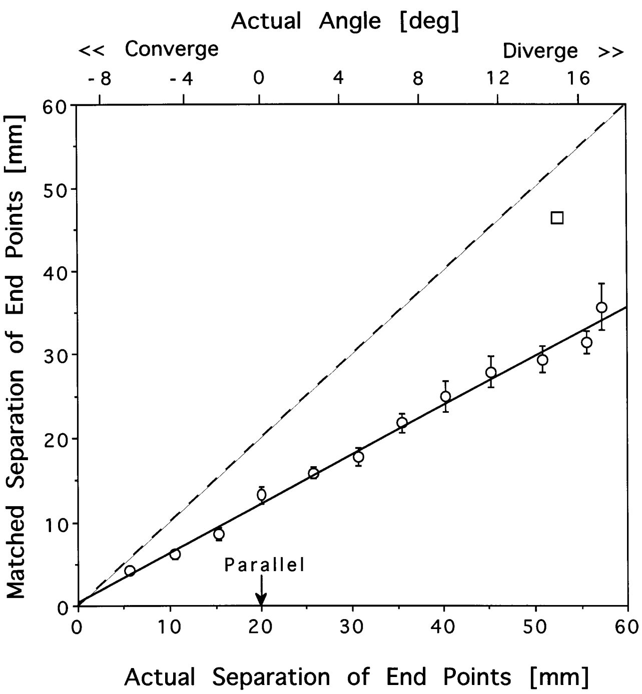

Fig. 6. Matched separation of a pair of rotating parallel lines (see Fig. 1c). Lines appeared to converge strongly toward the edge of the disk. Compression is given by the difference between the unit line (dashed) and the continuous line. Slope of the regression line is 0.61. The open square is equivalent to the first datum point in Fig. 2a for an actual sector size of 15° (12° matched sector size). The arrow marks the actual 20 mm separation of the two lines when parallel. The scale on the top gives the angle between the two lines from their point of theoretical intersection. Data points are averages of three matches by each of four observers ($n = 12$). Error bars equal ± 1 S.E.

6.1. Results and discussion

Results are shown in Fig. 6 where matched separation between the peripheral tips of the two lines is plotted against actual separation. If there were no illusion, all data points would lie along the dashed line of unit slope. In fact, data are fitted by a regression line of slope 0.61. This finding reflects the strong apparent convergence of the lines toward the edge of the disk and is consistent with a substantial compression of the space between the lines. Truly parallel lines 20 mm apart at their end points seemed to converge to an apparent separation of only 13 mm, while observers judged the lines to be subjectively parallel when, in fact, their ends were separated by as much as 33 mm. This is more than half as large again as their separation at the center, such that the lines diverged toward the periphery at an angle of about 6°. Note that the full range of separations (given in ° on the top) corresponds only to the very first portion of the abscissa in Fig. 2a. If one were to predict the matched separation of the end points (in mm) for an actual sector size of 15° (first datum point in Fig. 2a), one would obtain the square in Fig. 6. This separation suggests a much smaller compression in Experiment 1 than in Experiment 4, at least for small sector sizes.

There are two possible factors at work: (1) we showed above that subjective compression increases with speed of rotation (Fig. 3b). This was also reported by Ansbacher (1944) for a trans-illuminated arc, however, only for speeds not exceeding 1.3 rps (viewed from a distance of 3 ft). (2) Day (1973) showed that subjective compression increases with retinal eccentricity. The tips of the two rotating lines have a higher linear velocity than the more central parts of the lines, and they also lie at a greater eccentricity (4°).

Our experiment does not distinguish between these two possibilities, so we set up a qualitative demonstration of two counter-rotating disks with a fixation point between them (Fig. 7) by simply mounting a mirror next to one rotating disk. Each disk bore pairs of parallel lines in the form of a cross. As before the tips of the rotating lines moved with the highest velocity, but now they also passed near to the fovea so they possessed very little eccentricity. The predictions from the velocity hypothesis and from the eccentricity hypothesis are shown diagrammatically in Fig. 7.

All of our three observers selected the first of these two possibilities (b), with the rapidly moving tips still appearing to be close together, even near the fovea. This finding suggests that the perceived convergence of the two lines is due to the greater velocity at the edge, not to retinal eccentricity.

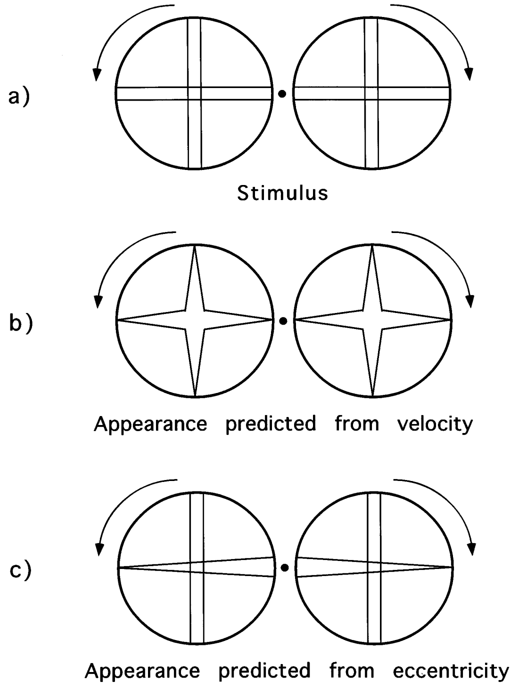

Fig. 7. Qualitative demonstration of the cause of apparent convergence of two rotating parallel lines in Experiment 4. (a) Two counter-rotating disks each bore pairs of parallel lines in the form of a cross. They were produced by positioning a mirror next to a rotating disk and fixating at its edge (black dot). If the subjective convergence of the lines were due to faster linear velocity towards the edge, observers should, and in fact did, report pattern (b). Conversely, if convergence of the lines were due to increasing retinal eccentricity, they would be expected to report pattern (c), but they did not. Conclusion: velocity, rather than eccentricity, explains the effect.

7. General discussion

Contrary to Ansbacher (1944) and Day (1973) who for narrow arc stimuli reported either uniform shrinkage (telescoping) or shrinkage of the trailing end, we here describe compression of the leading and trailing ends of a rotating sector with expansion in between. However, there is a difference in perception of a given sector if divided by one radial probe line only as opposed to the same sector divided by several lines. We used one radial line to avoid any apparent distortions that may be inherent with several dividers (Chen, Bedell & Ögmen, 1995). The task of matching the size of a single sector (Experiment 1) is different from adjusting the position of a single black probe line within that same sector (Experiment 3) as this second task requires matching the relationship between two subsectors. For this reason, it is not feasible to predict the form of the data in Experiment 3 from those obtained in Experiment 1.

All our effects are relatively small compared to the early results by Brown (1937), Ansbacher (1944), and Stanley (1966); but they are in the same order of magnitude as those by Marshall and Stanley (1964) and Day (1973). Table 1 suggests that these differences in size are accounted for not by the contrast, but the lower luminance of our stimuli, in addition to the smaller retinal eccentricity and difference in stimulus shape (arc versus sector).

7.1. Masking

An increase of apparent shrinkage with increasing illumination was already suggested by Ansbacher (1944) and would also explain the large difference (see Table 2) between reflected versus trans-illuminated arc stimuli reported by Marshall and Stanley (1964) and Stanley (1966). An effect of stimulus intensity would further agree with the results of Day (1973) obtained with increasing versus decreasing luminance gradients (22 versus 51% shrinkage). Another factor appears to be effective stimulus duration. In Experiment 2, we found an increase of apparent compression with increasing sector width up to about 200 ms (Fig. 3a). Consistent with this observation, Ansbacher (1944) reported little contraction with a non-concentric arc, when the trailing section of the stimulus did not follow in the same path as the leading section. Both intensity and duration suggest an explanation of the contraction effect in terms of neural de-sensitization.

However, given the relatively dim sectors used in our experiments, it is not evident how the leading portion of the stimulus might render the trailing portion invisible, and vice versa. A transient threshold elevation by rapid light adaptation (Baker, 1949) operates over too short a period of time and is too small to significantly affect visibility. Alternatively, suppression by forward masking (Day, 1973; Breitmeyer & Ganz, 1976) would be compatible with the inverted U-shaped function in Fig. 3a, but to our knowledge has not been demonstrated to occur with a single uniform stimulus (arc, sector) recurring periodically due to rotation.

7.2. Deblurring

What then could cause the apparent foreshortening of objects in motion? Let us compare our motion shortening to a possible motion deblurring mechanism. The visual system's integrating time of about 120 ms (Barlow, 1958) improves visual sensitivity for stationary objects, but it degrades the visibility of moving objects by blurring them. Burr (1980) found that when dots moved at speeds between 2.7 and 15°/s, the apparent length of their motion streaks increased with exposure times up to 30 ms, but between 30 and 120 ms the apparent length of the streaks decreased with increasing duration. The fact that the dot stimuli looked shorter when they moved further suggests an active mechanism for suppressing blur.

Morgan and Benton (1989) argued against this, and recently Burr and Morgan (1997) re-examined this question to see whether any such blur mechanism would improve the visual discrimination of objects. They measured blur discrimination thresholds for moving Gaussian-blurred edges and bars. The observer's task was to decide which of two moving stimuli, presented successively, was the more blurred. It is known that for stationary objects the just-noticeable difference in blur increases with baseline blur therefore, if motion increases blur, it would be expected to increase the just-noticeable difference in blur. An active deblurring mechanism, on the other hand, would be expected to counteract the detrimental effects of motion blur on discrimination performance. They found, however, that motion increased thresholds for blur discrimination, both for brief (40 ms) and for longer (150 ms) exposures. Burr and Morgan (1997) concluded that motion deblurring is a subjective effect, which does not enhance visual discrimination performance. According to these authors, moving objects appear sharp, not because of some special mechanism that removes blur, but because the spatial resolution of the motion detectors in the visual system (Anderson, 1993) is insufficient to decide whether a moving object is really sharp or not.

The results in Fig. 2b provide further evidence that deblurring may be ruled out as an explanation for motion shortening. For small sectors up to 40°, the difference in apparent compression for a white versus a black sector was relatively small, becoming progressively larger with increasing sector width. It therefore is unlikely that compression can be accounted for by a differential effect of deblurring for the leading and trailing edges, as such an effect would have to be inverted for a black sector (Burr, personal communication). Similarly, an explanation based on an asymmetry in the visual persistence of a black-to-white versus white-to-black edge leading to a mislocalization of the leading and trailing edges (including any internal divider) would require additional assumptions and therefore was not attempted.

7.3. Foreshortening

Many authors have overlooked the fact that motion deblurring is not necessarily equivalent to motion shortening, but both concepts are worth exploring. The argument of Burr and Morgan (1997) does not rule out the possibility that our foreshortening effect is actually the result of an active motion correcting process which does not have any effect upon blur discrimination, but simply makes moving objects look approximately the right shape and size by perceptually foreshortening them.

Our proposed foreshortening process will make a bowler's moving arm look about the right thickness, even if it does not help us to discriminate a sharp moving arm from a blurry furry one. Thus, we conjecture that our results, and those of Burr (1980) can be attributed not to a motion de-blurring, but to a motion de-lengthening mechanism.

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