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The spacing illusion: a spatial aperture problem?

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Abstract. A geometrical illusion in which the horizontal spacing between adjacent parallel lines in a row is underestimated when the lines are tilted away from vertical in a chevron configuration was investigated in two experiments. The perceived spacing was found to decrease as the tilt angle increased, consistent with the idea that separation judgements are influenced by the normal spacing between lines ie at right angles to the line orientation. It is proposed that this illusion reveals an analogue in spatial perception to the well-known aperture problem in motion perception. In establishing the separation of nearby or overlapping shapes in an image, the visual system cannot only rely upon the normal separation of contours belonging to each shape (as would be visible through small spatial apertures or receptive fields), since this varies with contour orientation. The system is therefore faced with a spatial aperture problem. The spacing illusion may arise because information usually available to solve the problem is absent in the illusion figure, or it may reflect a bias in favour of the orthogonal, which is adopted in the face of the ambiguity.

1 Introduction

The experiments reported here investigate a geometrical illusion in which observers underestimate the distance between adjacent parallel lines. In the configuration shown in figure 1, compare the horizontal distance between adjacent vertical lines (top) with the horizontal distance between the tilted lines (middle and bottom). Although the separation is actually the same for all sets of lines, it is underestimated for the tilted lines, and the underestimation increases as the angle of tilt increases.

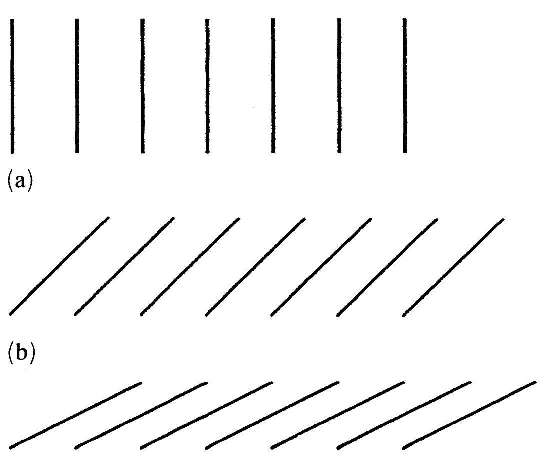

Figure 1. The spacing illusion. Three sets of parallel lines are shown; in (a) the lines are vertical, in (b) the lines are tilted at 45°, and in (c) the lines are tilted at 67.5°. Although the horizontal spacing is the same in all three sets of lines, it is apparently reduced in the tilted lines, and the reduction increases with tilt angle.

The illusion is probably the same as one reported by Judd in 1899 (described in more detail below). A straightforward interpretation is that the judgements of horizontal separation are influenced by the orthogonal distance between adjacent lines (ie the distance at right angles to their orientation). Orthogonal separation decreases steadily as angular tilt increases. Two parametric experiments were carried out using different procedures to measure the extent of this underestimation and its variation with angle and with the separation between adjacent lines. In one experiment, conducted at Sussex University, the method of constant stimuli was used on a single subject. In the other experiment, conducted at York University, the method of adjustment was used on two hundred and ten subjects.

2 Experiment 1

2.1 *Method*

2.1.1 *Subjects.* One of the authors (AO'H) served as the subject.

2.1.2 *Apparatus.* Stimuli were generated on an Amiga microcomputer. The display was made up of 640 × 400 picture elements or pixels, each measuring 0.38 mm in diameter (2 min arc at the viewing distance of 640 mm).

The stimulus field consisted of two horizontal rows of bright lines (119 cd m^{-2}, 1 pixel wide), presented one above the other against a dark background (0.27 cd m^{-2}). One row always contained vertical lines (the comparison stimulus), the other row contained lines tilted at one of sixteen different angles (the test stimulus). Individual lines were 60 pixels in length (2.04 deg arc), and the vertical separation between the two rows of lines (measured from the midpoint of the lines) was 8.8 deg arc.

Each line within a stimulus set was separated from its neighbour by the same horizontal distance or spacing. On a given trial the spacing of the test-stimulus lines (X_t) was set to one of the following: 10, 20, 30, 40, or 50 pixels (0.33, 0.68, 1.0, 1.37, and 1.68 deg arc, respectively). The spacing of the vertical comparison-stimulus lines (X_c) could be any one of a range of values, from $X_t - 0.2$ to $X_t + 0.07$ deg arc in steps of 0.07 deg arc.

The test-stimulus lines could be rotated about their midpoint to lie at one of the following angles to the vertical in any one trial: 0°, 5°, 10°, 15°, 20°, 25°, 30°, 35°, 40°, 45°, 50°, 55°, 60°, 65°, 70°, or 75°. The direction of rotation (clockwise or anticlockwise) varied randomly from trial to trial.

2.1.3 *Design and procedure.* The method of constant stimuli was used. The subject served in eighty conditions consisting of all five possible spacings of the test stimulus and all sixteen test orientations. Each condition involved twenty presentations of the comparison stimulus at each of five separations, from $X_t - 6$ to $X_t + 2$ pixels. This made a total of 100 trials per condition and 8000 trials for the experiment.

On each trial one set of stimulus lines extended rightwards from the bottom left of the stimulus field and the other set extended leftwards from the top right of the stimulus field. Which set of stimulus lines (test or comparison) appeared where (bottom left or top right) varied randomly from trial to trial. The horizontal distance separating the first and last lines within a particular set of stimulus lines varied at random between 400 and 500 pixels from trial to trial so that the number of lines in each stimulus set was not fixed but varied from trial to trial (and both for test stimuli and for comparison stimuli independently).

The subject's task was to decide in which set of lines the horizontal spacing between the ends of adjacent lines was greater. The subject pressed a response key on the left of the keyboard if the spacing between the lines at the bottom left of the stimulus field appeared greater, and a response key on the right of the keyboard if the spacing between the lines at top right of the stimulus field appeared greater. Where no difference in the spacing of adjacent lines for the two stimuli was apparent, the subject pressed either key at random. Both stimuli remained on-screen until the subject pressed one or other of the two response keys—which cleared the screen and started the next trial. The computer recorded the response to each stimulus.

Data were gathered over ten experimental sessions. Trials in different conditions were presented in random order, with the restriction that all conditions were equally represented in each session.

2.2 *Results*

At each test spacing and angle, a psychometric function was obtained from the percentage of 'wider' responses as a function of comparison separation. The 50% point of the function gives the comparison spacing at which comparison (vertical) and test (tilted) spacing were judged to be equal [the point of subjective equality (PSE)]. Logit analysis (Berkson 1953) was used to estimate the PSE for the psychometric function generated in each condition of spacing and of angle. Thresholds, defined as the reciprocal of the slope of the function at the PSE, were also calculated. The analysis included a chi-squared goodness-of-fit test for normality of the function. Some conditions produced significant departures from normality, and the data from those conditions were discarded. (Most of the conditions with the smallest separation yielded significant departures from normality.)

Figure 2 shows PSE, expressed as a percentage of test spacing, as a function of test orientation for different test spacings. The curves for different spacings appear to overlap. There was a tendency to underestimate the horizontal spacing between the end points of the test-stimulus lines, and this tendency increased as the lines departed further from vertical. Underestimation was greatest (between 6% and 9%) for departures of between 50° and 70°. There was a small tendency for spacings near to vertical to be overestimated by about 1% (allowing for the constant error evident in judgements of vertical test lines). Thresholds showed no consistent variation in sensitivity at different spacings and angles. However, thresholds for stimuli near vertical (less than 15°–20° tilt), were larger than thresholds for stimuli further from vertical (2.7 min arc and 1.9 min arc respectively).

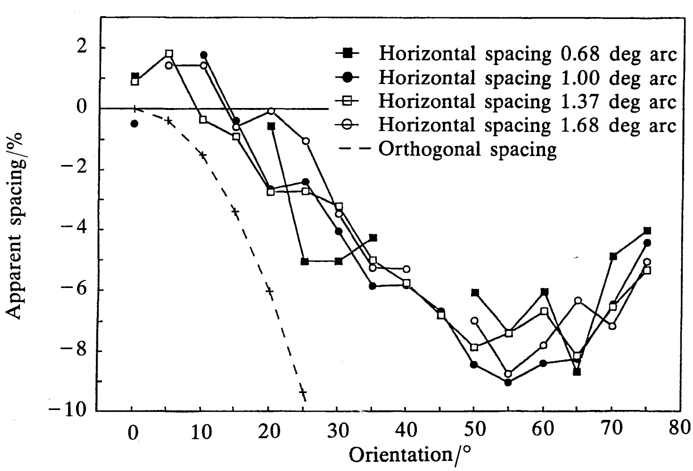

Figure 2. Results of experiment 1, from one subject, showing apparent spacing of the test lines as a function of their orientation relative to vertical. The apparent spacing (the point of subjective equality) is expressed as a percentage of the actual spacing, thus negative values are underestimations. Different curves represent different actual spacings. Data points were derived from psychometric functions using Logit analysis. Points from abnormal functions (as assessed by a chi-squared test) are not plotted. The dashed function shows the actual orthogonal spacing of the test lines as a function of orientation.

Also shown in figure 2 (dashed function) is the percentage underestimation that could be expected if spacing judgements were being made purely on the basis of the orthogonal distance between adjacent lines rather than on the basis of the horizontal spacing. The magnitude of the illusion is consistently smaller than that predicted solely on the basis of orthogonal separation.

3 Experiment 2

3.1 *Method*

3.1.1 *Subjects.* Two hundred and ten undergraduate students at York University served as subjects.

3.1.2 *Apparatus.* Stimulus lines were laser printed in black at 300 dots per inch on two sheets of white paper. One sheet contained five samples of parallel lines which served as test stimuli. Each sample was a patch 10 mm high and 40 mm wide, and the horizontal spacing between adjacent lines was always 2 mm. The lines in each sample were tilted to the left or right of vertical at the following angles: 0°, 22°, 45°, 56°, and 68°. For each subject half of the test samples were tilted to the left of vertical and half tilted to the right, with the direction of tilt counterbalanced across subjects. The second sheet of paper contained 41 numbered comparison samples of vertical lines, with horizontal spacings ranging from 30% to 110% relative to test spacing of 2 mm, in steps of 2%. Each sample contained twenty-six lines (10 mm high), and the samples were arranged in order of increasing comparison spacing.

3.1.3 *Procedure.* Each subject was given one sheet of test lines and one sheet of comparison lines, and was instructed to look at each test sample and to judge the horizontal separation between the adjacent lines. The task was to select the comparison sample which appeared to match the horizontal spacing of the tilted test lines, and to write the identification number corresponding to that comparison sample next to the test sample.

3.2 *Results*

Mean comparison spacing as a function of test spacing is shown in figure 3. Standard error bars are not shown because they were all below 0.75%, ie smaller than the symbols. Since the horizontal spacings between tilted test lines were the same for all orientations, veridical judgements would lie on a horizontal line at 100%. If the subjects were responding according to the orthogonal separation of the lines, then judgements would lie along the cos function drawn as a dotted curve in figure 3.

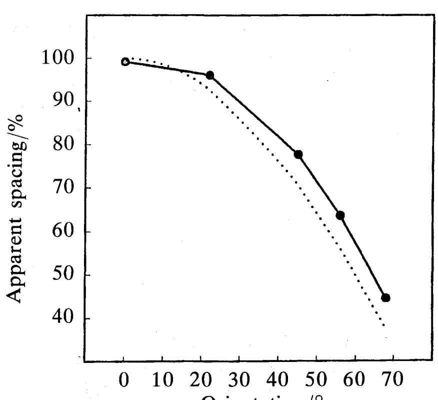

Figure 3. Results of experiment 3, from two hundred and ten subjects, showing apparent spacing (expressed as a percentage of actual spacing) as a function of orientation relative to vertical. The dotted function shows the actual orthogonal spacing as a function of orientation.

It can be seen from the figure that orthogonal spacing was a good predictor of performance—judged separations are only slightly larger than the predictions. There was no tendency to overestimate test spacing, but this only occurred at test angles below 15° in experiment 1, and the smallest angle employed in experiment 2 was 22°.

4 General discussion

The results of the two experiments clearly show that the separation of oblique lines is underestimated. The method of constant stimuli produced more conservative estimates of illusion magnitude than did the variant of the method of adjustment. Morgan et al (1990) have recently reported a similar illusion using 'H' configuration stimuli in an interval estimation task (figure 4a). Using a modified method of constant stimuli, they found that the length of the horizontal bar across the H was underestimated by about 4% when the sides were tilted at 45°. The results of Morgan et al are therefore comparable with those from experiment 1, using a similar method. As mentioned in section 1, Judd (1899) reported a similar illusion. He obtained underestimations of between 12% and 29% using the configuration in figure 4b (45° tilt) and the method of adjustment. Judd's illusion magnitudes are comparable with those found in experiment 2 at 45° tilts (22.3% underestimation).

Parametric data presented here show that the extent of the illusion increases as the angle of tilt increases, supporting the view that orthogonal separation influences perceived separation. Data from experiment 1 show a flattening in illusion strength at tilts greater than about 60° from vertical. This may reflect limitations in the display: as tilt increased the lines took on an increasingly jagged appearance, due to the resolution limits of the display, and this may have interfered with judgements. The flattening was not observed in experiment 2 which used stimuli plotted at much higher resolution. Experiment 1 found slight (1%) overestimations of spacing at small test angles. The reasons for this overestimation are not clear, though judgements were

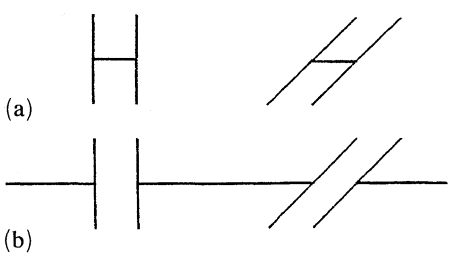

Figure 4. Other configurations of the spacing illusion. In (a), used by Morgan et al (1990), the observer judged the length of the crossbar of the H. In (b), used by Judd (1899), the observer judged the gap between the intersections. The crossbar or gap is underestimated when the inducing lines on either side are tilted away from vertical.

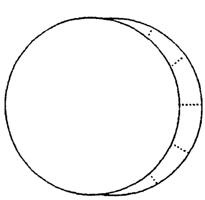

Figure 5. The spatial aperture problem. Two partially overlapping discs are shown, perhaps representing two coins lying one on top of the other. How far apart are they, and in what direction is the displacement? Local information about orthogonal separation of roughly parallel contours belonging to each disc is ambiguous, because the separation varies with orientation (dotted lines). An additional step is required to arrive at a single estimate of separation; in this case one could take the maximum separation signalled around the circumference.

more difficult at these small angles, as witnessed by the number of data points (five) not plotted because their psychometric functions were abnormal. A possible reason for the difficulties at angles near vertical may lie in the jagged appearance of lines just off the vertical, as mentioned above for lines near horizontal.

Spatial-frequency-selective cells in the visual system are well suited to provide information about orthogonal separation between parallel lines. However, when the visual system is faced with the task of establishing the separation of different shapes in natural images, orthogonal separation of contours is insufficient. Consider, for example, the shapes in figure 5, representing two coins lying one on top of the other. Viewed through sufficiently small apertures adjacent contours belonging to each coin are approximately parallel, but their orthogonal separation varies with position (dotted lines), so the outputs of individual cells tuned to different separations cannot establish the true separation of the coins. The system is faced with a spatial aperture problem which is analogous to the aperture problem in motion processing—local motion detectors can only signal movement velocity orthogonal to a contour moving through their receptive field, and the true movement of shapes in the image is thought to be established by integrating information across many detectors (eg Hildreth 1984). To solve the spatial aperture problem, the system may integrate information from many spatial-frequency-selective cells tuned to different orientations (cf procedures proposed for solving the motion aperture problem), or it may make use of disambiguating information from, for instance, stereoscopic disparity or unusual features such as points of maximum curvature. Such information is absent in the illusion figure. Morgan et al (1990) have argued that, in the face of the inherent ambiguity in making separation judgements which we have described as a spatial aperture problem, a bias in favour of orthogonal separation would make sense functionally. In certain situations information about orthogonal separation is useful, in particular when making judgements about the widths of gaps. Humans and animals can judge accurately whether a gap is wide enough for them to walk or jump through (Lock and Collett 1980; Warren and Whang 1987), though orthogonal separation in the image would correspond straightforwardly to gap width only under frontoparallel viewing conditions.

In summary, we have presented data from two experiments using very different techniques which demonstrate the existence of a spacing illusion in spatial vision, similar to that originally reported by Judd (1899). The illusion was found to vary with the orthogonal separation between adjacent lines. It is interpreted as a consequence of the spatial aperture problem.

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