
Velocity constraints on apparent rotational movement

Joyce E Farrell¶

Department of Psychology, New York University, 6 Washington Place, 8th Floor, New York
NY 10003

Axel Larsen, Claus Bundesen

Department of Psychology, Copenhagen University, Njalsgade 90, DK-2300 Copenhagen S, Denmark
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Abstract. The visual illusion of apparent rigid rotation was produced by sequential alternation of two views of the same object in different orientations. The minimum stimulus-onset asynchrony required for the appearance of rigid rotation was a linearly increasing function of the angular difference in orientation between the two views. Variation in the size of the object affected the zero-intercept of the function, but the slope was virtually constant. The slope invariance suggests that the appearance of rigid rotation is constrained by an upper bound on the apparent angular velocity of the object as a whole, rather than a bound on the linear velocity of its parts.

1 Introduction

Illusory movement can be created by successively displaying a stationary object in different positions. In 1875 Exner reported that when a spot of light is presented first in one position and, after an appropriate time interval, again in a second position, observers perceive the spot to translate through the shortest path connecting its successive positions (cf Boring 1942). A number of later studies (reviewed by Neff 1936; Aarons 1964; Kolers 1972) have further explored the spatiotemporal conditions for the perception of apparent continuous translation.

A famous conjecture known as Korte's (1915) third law is that if stimulus intensity and duration are held constant, the interstimulus interval required for optimal apparent translation is directly related to the distance separating the stimulus positions. Korte's third law has not stood the test of time (cf Neuhaus 1930; Kolers 1972; Caelli and Finlay 1981), but the data (eg Corbin 1942; Caelli et al 1978) have supported a related hypothesis, namely that the minimum temporal interval separating the onset of successive stimuli—the stimulus-onset asynchrony (cf Kahneman 1967; Kahneman and Wolman 1970) at the simultaneity threshold (Corbin's usage) for apparent movement—is a linearly increasing function of the spatial separation of the stimuli. Results by Corbin (1942) and Attneave and Block (1973) suggest that the effective spatial separation is the apparent distal separation between the stimuli in three-dimensional space, rather than the proximal separation in the two dimensions of the visual field.

Early studies (eg Wertheimer 1912) also showed that when a line is rapidly presented in two successive orientations, observers perceive the line to rotate through the smallest angle separating the two orientations. However, until recently the spatiotemporal conditions for apparent rotation movement had not been investigated. In 1976 Shepard and Judd found that the minimum stimulus-onset asynchrony required for apparent rigid rotation was a linearly increasing function of the angular difference in orientation between the stimuli. Moreover, the linear function was nearly identical for perceived rotations in depth and in the picture plane, indicating again that the stimulus onset-onset times required for apparent rotations are dependent on the three-dimensional appearance of the stimuli.

¶ Author to whom requests for reprints should be addressed.

The linear functions relating the temporal interval required for the illusion of movement to the perceived separation of successive stimuli (cf Corbin 1942; Shepard and Judd 1976) have positive intercepts and slopes. One interpretation of these findings is that successive stimuli are first represented as successive views of the same object and then transformed into one another by interpolation of a path connecting the stimuli (cf Beck et al 1977; Shepard 1981): positive intercepts measure the time to encode stimuli as different views of the same object and positive slopes measure velocity limits on the process of path interpolation.

Assuming that there is a limit on the linear velocity of an apparently moving object, we performed the present experiment to clarify the nature of the velocity limit on apparent rotational movement. If the rate of apparent rotation of an object is limited by an upper bound on the linear velocity of the points or elements of the object, then the minimum stimulus-onset asynchrony for apparent rigid rotation should be a linear function of the length of the trajectory of a point or element moving farthest from the center of rotation and therefore a linear function of the angular extent of the transformation of the object, as found by Shepard and Judd (1976). An alternative interpretation of Shepard and Judd's findings is that apparent rotation is constrained by an upper bound on the *angular* velocity of the apparently rotating object. To test these interpretations we contrasted the effects of path length and rotational angle simply by varying the size of the stimulus pattern independently of the difference in angular orientation. In a separate control condition we tested for possible effects of stimulus size on functions relating the minimum stimulus-onset asynchrony required for apparent rigid translation to the spatial separation between stimuli.

2 Method

2.1 Main condition

2.1.1 *Subjects.* Eight students at Copenhagen University and two of the authors (JEF and AL) served as subjects. All subjects had normal or corrected-to-normal vision.

2.1.2 *Stimuli and apparatus.* The stimuli were size-scaled and rotated versions of the prototype pattern shown in figure 1. The pattern was scaled by geometric multiplication with a factor of 1, 2, 3, or 4. For each size of the pattern, forty-eight stimulus pairs were constructed by combining different transforms obtained by picture-plane rotations about the base of the pattern (see figure 1). The difference in angular orientation between the two members of a pair (v) was either 30, 60, 90, or 120°. Each of these four values was represented by twelve ordered combinations of orientations given by $[(u, \text{mod}(u+v, 360^\circ))]$, for $u = 0, 30, \dots, 330^\circ$. The whole set of one hundred and ninety-two stimulus pairs was arranged in a random order of presentation.

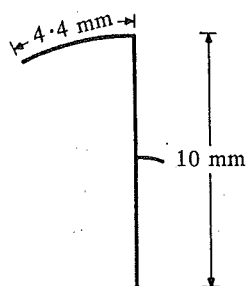


Figure 1. Prototype stimulus pattern. (The two curved elements are parts of circles centered at the lower endpoint of the vertical bar. This lower endpoint is referred to as the base of the pattern.)

The stimuli were displayed on a computer-driven cathode ray screen (Tektronix 604 Monitor equipped with a P31 phosphor) by periodic intensifications at a rate of 40 Hz, each with a luminous directional energy (cf Sperling 1971) of approximately $0.6 \text{ cd } \mu\text{s cm}^{-1}$; the background luminance of the screen was about 0.5 cd m^{-2} . The subject viewed the display binocularly from a distance of 1 m. At this viewing distance the prototype pattern, scaled by a factor of 1, 2, 3, or 4, subtended a visual angle of 0.57, 1.15, 1.72, or 2.29 deg, respectively. The base of the pattern always appeared at the center of the screen, but fixation was free.

2.1.3 Procedure. On each trial the two stimuli in a pair were displayed in sequential alternation with a constant interstimulus interval of 50 ms. The interstimulus interval ensured that the phosphor image trace of the display had decayed before the presentation of the alternate image. The possibility of masking effects was further reduced by the fact that there was no overlap between stimuli within the same pair.

The stimulus-onset asynchrony (SOA) was initialized at 1050 ms. At this rate of alternation the pair of stimuli created a visual impression of a single object rocking to-and-fro in the picture plane while preserving its shape. If the subject pressed a right-hand key, the SOA was decreased by one eleventh. The subject was instructed to press this key repeatedly until a limit was reached at which the visual impression of rigid movement disappeared. The limiting value of SOA (SOA_1) was registered by pressing a center key. By then pressing a left-hand key the SOA was increased by one tenth, which the subject was instructed to do repeatedly until the visual impression of rigid movement reappeared. The limiting value of SOA (SOA_2) was again registered by pressing the center key, which also terminated the trial.

Trials were presented in blocks of thirty-two, and subjects were encouraged to rest between blocks. The entire set of six blocks took three to four 90 min sessions, depending on the subject.

2.2 Control condition

Three new subjects (students with normal vision) and one of the authors (AL) participated as observers in the control condition. The stimuli were size-scaled versions of the prototype pattern (see figure 1), generated by geometric multiplication with a factor of 1 or 4. Either size was used in three types of stimulus pairs such that a pair consisted of two alternating patterns that were identical up to a horizontal displacement measuring 26, 39, or 52 mm on the screen, corresponding to 2, 3, or 4 deg of visual angle at a viewing distance of 0.75 m. Each combination of size (1 or 4) \times displacement (2, 3, or 4 deg) was represented by fifteen identical replications, and the whole set of ninety stimulus pairs was arranged in a random order of presentation. A steady fixation point was provided by a dot appearing 13 mm (1 deg of visual angle) below the midpoint of an imaginary line segment connecting the bases of the two patterns in a pair. Trials were run in three blocks of thirty during a single 90 min session. In all other respects apparatus and procedure were the same as in the main condition.

3 Results

3.1 Main condition

As expected from preliminary explorations with various types of stimulus patterns, the stimuli used in the main condition favored the appearance of rigid rotation in the picture plane. Subjects unanimously reported that when apparent rigid movement of the stimulus pattern was seen, that movement was a rigid rotation confined to the picture plane. Near the threshold for apparent rigid movement the impression of rigid rotation competed with impressions of partial rotation and/or flicker. A sample

report of partial rotation and flicker was that the straight line of the pattern appeared to rotate while the curved sector elements simply flickered.

For both the breakdown and the subsequent reemergence of apparent rigid rotation, the critical SOAs increased linearly with the angular difference in orientation between

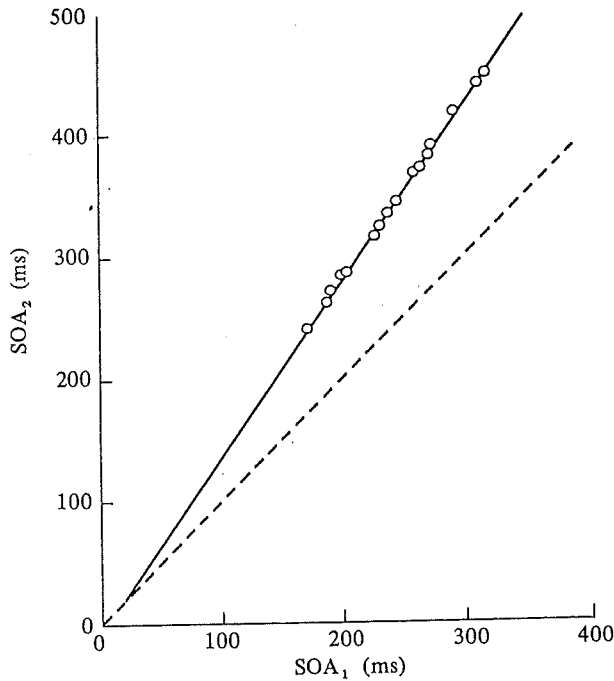


Figure 2. Correlation between group means of SOA_1 and SOA_2 . Data are fitted by a solid regression line; a dotted reference line indicates where SOA_2 equals SOA_1 .

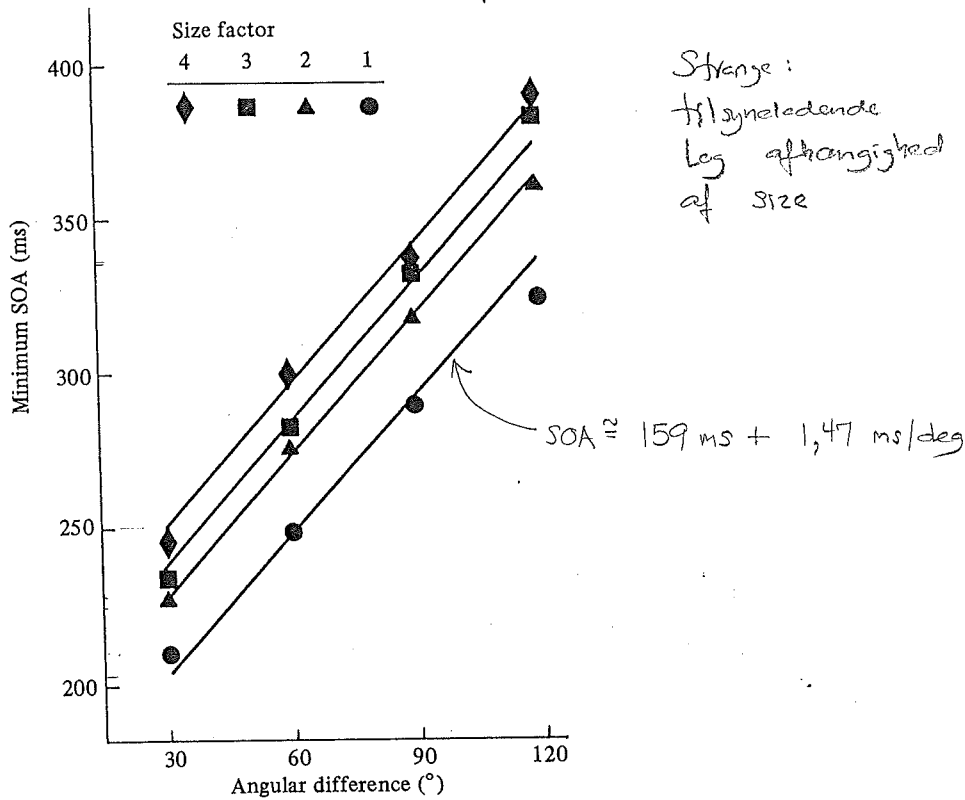


Figure 3. Group means of minimum SOA as a function of the angular difference in orientation between the stimuli with stimulus size (4 = large) as the parameter.

the two views of the stimulus pattern. As shown in figure 2, SOA_2 was approximately a linear function of SOA_1 with a slope of 1.43; the product-moment correlation was 0.999. In figure 3, the average of SOA_1 and SOA_2 , referred to as 'minimum SOA', is plotted as a function of angular difference in orientation with size of the pattern as the parameter. As can be seen, the effect of size was rather small in comparison to the large effect of angular difference in orientation.

We tested the hypothesis that apparent rotation is constrained by an upper bound on angular velocity by fitting linear functions relating minimum SOA and angular difference in orientation. Separate linear functions were fitted to the data for each size of the pattern with the constraint that the slopes of the lines be the same. The best-fitting functions, superimposed on the data in figure 3, accounted for 99% of the variance. The deviations between the data and the theoretical functions did not reach significance, $\chi^2(11) = 18.47$, $p = 0.08$.

We also tested the hypothesis that apparent rotation is constrained by an upper bound on the linear velocities of points or elements of the apparently rotating object. The length of the trajectory of any point of the pattern was directly proportional to the product of the angle of rotation and the factor (1, 2, 3, or 4) by which the pattern was scaled. On the hypothesis in question, then, the theoretical functions are four lines, one for each size of the pattern, such that the slopes of the lines are proportional to the size of the pattern. The best-fitting functions accounted for 88% of the variance; the deviations between the data and the theoretical functions were highly significant, $\chi^2(11) = 234.59$, $p < 10^{-9}$.

3.2 Control condition

For either size of the stimulus pattern the minimum SOA required for apparent rigid translation was approximately a linear function of the horizontal displacement, and the effects of stimulus size and horizontal displacement were approximately additive. For size 1 minimum SOA averaged 238, 254, and 267 ms for horizontal displacements of 2, 3, and 4 deg, respectively. For size 4 the corresponding values were 223, 243, and 253 ms. Fitting these data by two parallel lines, one for each stimulus size, accounted for 98% of the variance; the departures from the theoretical functions were not significant, $\chi^2(3) = 0.44$, $p = 0.93$.

((smaller SOAs for size 4?))

4 Discussion

Visual apparent translation is supposedly constrained by an upper bound on the linear velocity of the object apparently translating through space. The present results on apparent translation support the presumption that the constraint on linear velocity is independent of the size of the object. As measured by the rate of increase in minimum SOA as a function of horizontal displacement, the upper bound on linear velocity observed in this experiment was about $0.068 \text{ deg ms}^{-1}$ or 0.9 m s^{-1} .

Our results on apparent rotation—that minimum SOA varied linearly with the angle of rotation such that the slope of the function was approximately the same regardless of the size of the stimulus pattern—suggest that the rate of apparent rigid rotation is subject to another type of constraint, an upper bound on the angular velocity of the object apparently rotating in space. In the present experiment we observed a limit of approximately $0.68^\circ \text{ ms}^{-1}$ or 2 cycles s^{-1} .

Temporal effects of pattern size were additive with effects of horizontal displacement for apparent translation and with effects of angular disparity for apparent rotation. Additivity of temporal effects of two factors suggests that the effects are generated at different stages of processing (Sternberg 1969). The temporal effects of horizontal displacement and angular disparity were supposedly generated at a stage of internal interpolation of a path connecting successive stimuli. It seems likely that

the absolute size of the stimulus pattern influenced a stage of initial stimulus analysis, prior to the internal transformation of the visual representation of the object.

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