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Perception of motion in equiluminous kinematograms

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Abstract. Two fields of random dots that were identical except for a slight shift in a central square region were presented in rapid alternation. This produced a vivid impression of a square moving back and forth above the background. When the kinematogram is presented in equiluminous red/green, the motion of the central region can still be seen, although over a narrower range of alternation rates, interstimulus intervals, and displacements than for black/white presentation. The perception of motion for equiluminous stimuli indicates that colour and motion can be analyzed conjointly by the visual system. However, as originally reported by Ramachandran and Gregory, the segregation of the oscillating central square from the background is lost at equiluminance. This segregation process therefore appears to be colour-blind.

1 Introduction

Several authors have postulated parallel channels of luminance and chrominance information in the visual system (Hering 1878; Hurvich and Jameson 1957; Guth and Lodge 1973; King-Smith and Carden 1976; Ingling 1978). A number of effects previously reported for black/white stimuli have also been observed for stimuli defined only by colour contrast. The tilt aftereffect (Elsner 1978), spatial-frequency-specific threshold elevation (Yujiri et al 1980), and spatial-frequency shift (Favreau and Cavanagh 1981) have all been reported for equiluminous stimuli. In addition, it has been found that a spatial-frequency shift can be established in the chrominance channel simultaneously with a shift in the opposite direction in the luminance channel (Favreau and Cavanagh 1981), indicating a certain degree of independence between these two channels, at least for spatial-frequency information.

A number of other effects are not obtained, however: metacontrast (Bowen et al 1977); depth in random stereograms (Lu and Fender 1972; de Weert 1979; Gregory 1977); and the McCollough effect (Stromeyer and Dawson 1978; Mikaelian 1980). In addition, it has been suggested that the chrominance channel may be incapable of processing motion information. Zeki (1973), for example, has claimed that colour and motion are processed independently in separate regions of the prestriate cortex. Ramachandran and Gregory (1978) have reported that apparent motion is not perceived in kinematograms at equiluminance.

The absence of motion perception for equiluminous kinematograms would be consistent with Zeki's (1973) suggestion that cells sensitive to colour contrast are not responsive to motion. However, the reports of motion aftereffects contingent on stimulus colour (Lovegrove et al 1972; Mayhew and Anstis 1972; Favreau et al 1972) and colour aftereffects contingent on motion (Stromeyer and Mansfield 1970) indicate the presence of cells or channels selective for both colour and motion. In particular, Favreau (1976) has reported a colour-contingent motion aftereffect following adaption to rotating equiluminous coloured spirals. Physiological studies in the striate cortex of the monkey reveal that colour-sensitive cells do show some motion sensitivity (Gouras and Kruger 1979; Michael 1978). Although this evidence implies some combined analysis of colour and motion, it may not be as sensitive as that for luminance and motion. For example, a recent study (Cavanagh et al 1984) of drifting equiluminous sine-wave gratings showed that the perception of the motion of these stimuli, although possible, was severely degraded. Equiluminous stimuli may therefore provide only a weak input to motion perception, and perhaps motion might be seen even in equiluminous kinematograms if the viewing conditions were more favourable than those used by Ramachandran and Gregory (1978).

In the kinematogram (Anstis 1970; Julesz 1971), two successive fields of random black and white dots are used, both containing a square region of identically organized dots whose position differs slightly in the two fields. Rapid alternation between the two fields will give the impression of an oscillating square floating above the background if the displacement is small (Braddick 1974). This stimulus is of particular interest because the motion created by the alternation of the two fields defines the perceived form; there is no form visible in either of the individual fields alone. The perception of the form thus depends on a motion-analysis system that can compute the correlation between the two fields. This system has been labelled the 'short-range' motion system (Braddick 1974).

To study the kinematogram at equiluminance, Ramachandran and Gregory (1978) replaced the black and white areas of the random-dot field with red and green. They reported that when the red and green areas were adjusted to be of equal luminance, the motion of the central square, which was quite distinct in the stimulus with black and white areas, disappeared and the central square itself was indistinguishable from the background. The reduced acuity in the chrominance channels did not appear to be a contributing factor as, in all cases, the individual red and green dots of the stimulus patterns were clearly visible.

One important factor in their experiment may have interfered with the motion perception, however. Ramachandran and Gregory had a dark interstimulus interval (ISI) of 50 ms between the presentation of the two dot fields. Lappin and Bell (1976) and Braddick (1974) have shown that a dark ISI can significantly interfere with the motion perception in kinematograms and we hypothesized that this interference would be even greater for the relatively weak motion stimulus provided by the equiluminous presentation.

2 Experiment 1: The effect of dark-ISI duration

In the first experiment we measured the effect of dark-ISI duration on the perception of motion in the kinematogram. Observers were requested to report whether or not they perceived 'coherent motion' in the central area of the figure. Coherent motion was defined as motion of the central area all-of-a-piece, left and right. Any up, down, or diagonal motion, ambiguous motion, or motion of different regions in different directions was to be reported as no motion.

For each of a range of displacements of the central square the observers varied the red/green luminance ratio to determine the contrast range within which coherent motion disappeared. These measurements were repeated at several ISI values. The alternation rate was fixed (3.3 Hz); thus as ISI increased, the field exposure time decreased to maintain a constant total duration.

2.1 *Method*

The visual stimulus consisted of two red/green random-dot displays (128 × 128 elements, 27 deg × 27 deg, element size = 0.21 deg × 0.21 deg) within which a centrally located square (48 × 48 elements, 10 deg × 10 deg) was displaced horizontally in one field relative to the other. They were generated by a 512 × 512 colour graphics system and displayed on a Conrac 5411 monitor. The *x* and *y* CIE coordinates of the phosphors were 0.60 and 0.35 for red and 0.29 and 0.60 for green. Luminance constrast of 0% was defined for each subject by equalizing red and green luminances with the use of 10 deg uniform-field flicker photometry at 15 Hz. (This minimum flicker point serves as a reference value but is not necessarily the equiluminance point for the kinematogram which involves different spatial and temporal frequencies.) The displays had a mean luminance of 26 cd m^{-2} and the raster rate was 60 Hz.

A small white cross-hair (0.42 deg × 0.42 deg) was located in the centre. Four ISIs were used (0, 16, 33, and 50 ms, within the restrictions imposed by the TV raster), the intervening field being black (mean luminance 0.5 cd m^{-2}). For each of the ISIs, the exposure duration of the random-dot fields was adjusted so that the stimulus onset asynchrony (SOA) remained fixed at 150 ms (alternation rate of 3.3 Hz). The exposure durations were therefore 150, 133, 117, and 100 ms for the ISIs of 0, 17, 33, and 50 ms, respectively. The red/green contrast range for which no coherent motion could be seen was verified for eight different relative displacements of the central square between the two dot fields (0.054 to 0.42 deg in steps of 0.054 deg, that is, from $\frac{1}{4}$ to 2 element widths in steps of $\frac{1}{4}$ of an element).

Prior to the test trials, heterochromatic flicker photometry was used to set red/green to equiluminance. The experimenter then set the display to one of the four ISIs and proceeded to test all eight displacements at that rate. The observer was requested to fixate the stationary cross-hair within the oscillating central figure and to indicate: (i) when coherent motion disappeared, and (ii) when motion reappeared as a function of red/green contrast. To do so, the observer manipulated a joystick that controlled red/green contrast. Starting at red more luminous than green, the observer decreased red luminance (the program simultaneously increased green luminance, maintaining a constant mean luminance in the display) and reported when coherent motion had disappeared. The observer then continued to decrease the red luminance and reported when motion reappeared. Starting with green more luminous than red, the observer repeated the procedure, but now increased the red luminance until coherent motion disappeared. The observer then continued to increase the red luminance until motion reappeared. This procedure was repeated twice within each of the twelve blocks of trials, thus giving four readings at red more luminous than green and four readings at green more luminous than red. Each of the two groups of readings was averaged to give the upper and lower bounds defining the red/green contrast range for which coherent motion was not seen.

Two of the authors (PC and JB) served as subjects.

2.2 *Results*

The results are shown in figure 1. The data points indicate the contrasts at which the transition from coherent motion to no motion occurred. On moving up the graph from green more luminous than red (shown as negative contrast values) at a particular displacement, the first datum point encountered denotes the point at which coherent motion was lost. On continuing upward, the second point encountered (of the same ISI) denotes the contrast at which coherent motion returned. These two points—the upper and lower bounds for coherent motion—bracket the contrast range around equiluminance for which coherent motion is lost.

For example, in figure 1a for the 50 ms ISI condition and the shortest displacement, 0.054 deg, coherent motion is lost at − 13% (red 13% less luminous than green) and not regained until + 42% (red more luminous than green). The range of contrast around equiluminance for which coherent motion is not seen increases as the displacement is increased, reaching from − 35% to + 50% when the displacement is one dot element width (0.21 deg). This condition replicates the conditions of Ramachandran and Gregory's (1978) study.(1)

As the dark ISI was decreased, however, the no-motion range narrowed. In particular, for an ISI of 0 ms, there were several displacements for which the oscillating motion of

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(1) Because of a typographical error, the dot size in Ramachandran and Gregory's 1978 paper was reported as 3 deg. In fact, it was 0.3 deg.

the central square never disappeared no matter what the red/green luminance ratio. This occurred for displacements of less than one element width for JB and for less than $\frac{3}{4}$ of an element width for PC.

The dark ISI therefore appears to have interfered with the motion perception. When the ISI is set to zero (the two fields follow each other on consecutive TV frames), coherent motion can be clearly seen over small displacements.

Although coherent motion is perceived at equiluminance, the nature of the central square changes dramatically as was originally reported by Ramachandran and Gregory (1978). Rather than floating above the background, it appears merely to jiggle in the plane of the background. The sharp edges and corners delimiting its boundaries disappear, replaced by a blurred transition from the static background to the coherent central motion.

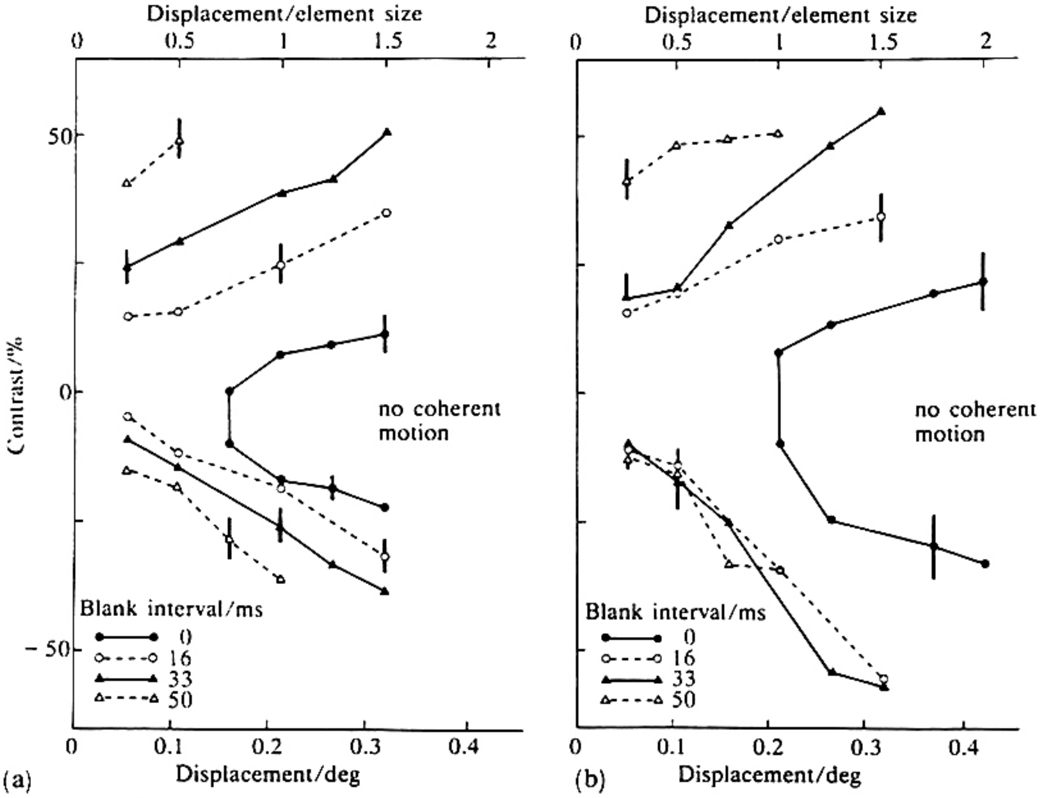

Figure 1. Red/green contrast ranges producing coherent-motion and no-motion reports as a function of ISI and displacement of the central square. The zero-contrast point is the preset equiluminance value. For each ISI, coherent motion is seen for red/green contrasts above the data points for that ISI in the top (red more luminous than green) portion and below the data points for that ISI in the bottom (green more luminous than red) portion. No motion is reported between these upper and lower bounds. Vertical bars show typical standard errors. The contrast is shown as the red luminance (R_{mod}) minus the green luminance (G_{mod}) divided by the sum of their mean luminances. (a) Observer JB; (b) observer PC.

3 Experiment 2: Element size

The size of the elements of the random-dot field appears to influence the maximum displacement for which motion can be seen in the kinematogram. Although Braddick (1974) has reported that the maximum displacement is 15 min independently of the element size, Lappin and Bell (1976) and Chang and Julesz (1983a) report that this maximum displacement increases directly with element size. We therefore examined the relation between displacement and element size for a luminance kinematogram (red and black elements) and an equiluminous kinematogram (red and green elements) to see whether there might be a fixed maximum displacement in either condition.

3.1 *Method*

Red and green, and red and black random-dot displays were each presented at five different element sizes (0.11 × 0.11, 0.21 × 0.21, 0.42 × 0.42, 0.85 × 0.85, and 1.70 deg × 1.70 deg). Two alternation rates were also used (2.5 and 3.3 Hz: 250 and 150 ms SOA). ISI was 0 ms throughout, apart from the unavoidable TV refresh rate. The central oscillating area was always 10 deg × 10 deg. The number of elements within the oscillating central square was reduced as element size increased in order to maintain a fixed visual angle (10 deg × 10 deg) for the central region. The number of elements in the central region was 96 × 96, 48 × 48, 24 × 24, 12 × 12, and 6 × 6 for element sizes 0.11, 0.21, 0.42, 0.85, and 1.70 deg, respectively. All other stimulus details were identical to those of experiment 1.

The experiment was divided into four blocks of trials, one block for each combination of colour (red/black or red/green) and alternation rate (2.5 and 3.3 Hz). The observers used a joystick to adjust the displacement over which the central square oscillated, and reported the maximum displacement for which coherent motion could just be seen. Two readings were taken starting from a small displacement and increasing the displacement until coherent motion disappeared, and two readings starting from a large displacement and decreasing until coherent motion reappeared.

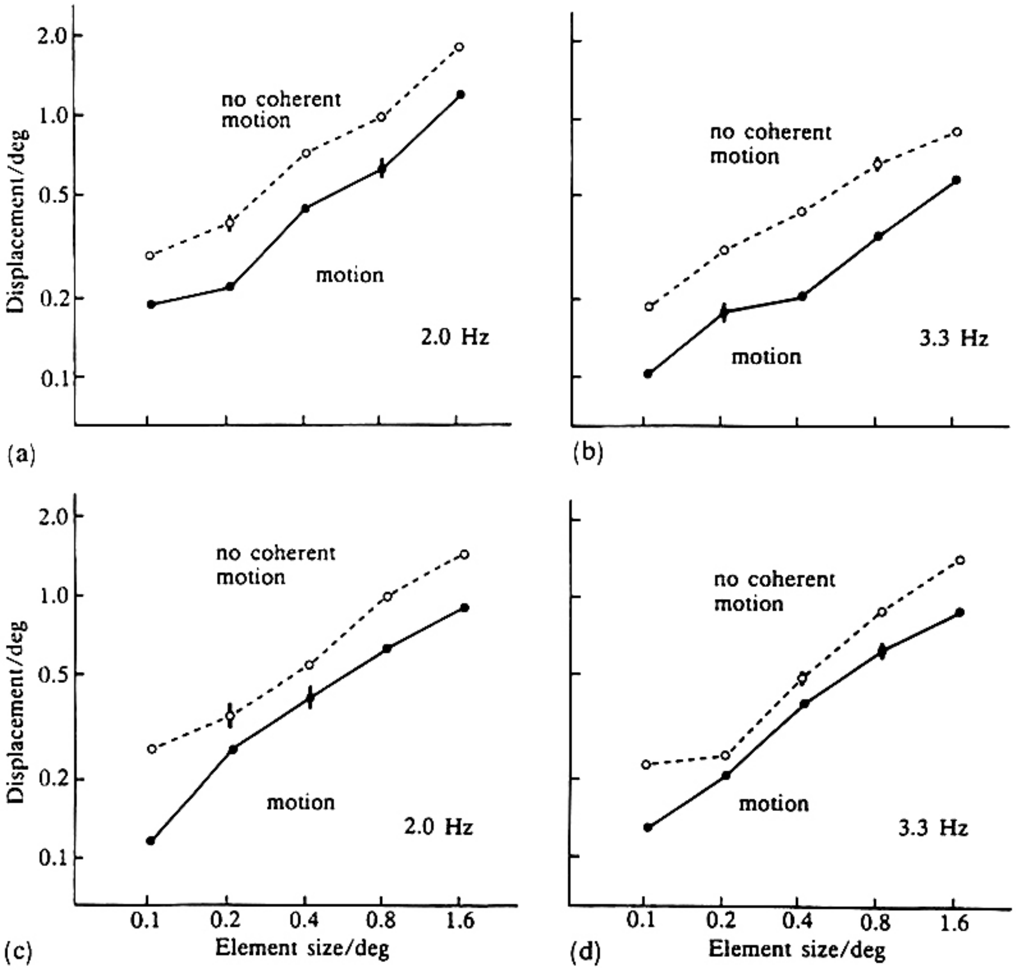

Figure 2. Maximum displacement at which coherent motion can still be seen as a function of element size. Data in panels (a) and (c) are for alternation rate of 2.0 Hz and those in panels (b) and (d) for 3.3 Hz. Empty circles represent the data for the luminance condition (red and black elements) and filled circles the equiluminance condition (red and green elements). Vertical lines show typical standard errors. (a) and (b) Observer JB; (c) and (d) observer CM.

The results of experiment 1 showed that the equiluminance point, the red/green contrast that minimized the largest displacement for which coherent motion could be seen (the leftmost tip of the 0 ms ISI curves in figures 1a and 1b) corresponded closely to the minimum flicker settings (the 0% luminance contrast point). Before the experiment began, equiluminance was therefore set for each observer by the minimum flicker procedure as described in experiment 1. As a control, the possibility that the equiluminance point might shift away from the preset value as a function of element size was evaluated for observer PC. Once the displacement at which motion just disappeared was located, the red/green contrast was swept up and down to determine the no-motion range. This range was expected to be narrow and centred on the preset equiluminance value. If some broader range was found, the midpoint of this range was recorded.

The observers were two of the authors (PC and JB) and a naive observer (CM).

3.2 *Results*

The results in figures 2 and 3 show that the maximum displacement at which coherent motion can be seen increases directly with element size. A displacement of one element width would trace a 45° diagonal line through a point slightly below the origin. The maximum displacements for the red/green equiluminous condition are generally close to this diagonal at both alternation rates. The maximum displacements for the red/black conditions are consistently above the red/green data, by a factor of two, on the average.

There appear to be no qualitative differences between the data for the kinematogram with (red/black) and without (red/green) luminance contrast except for this increase in the maximum displacement. If there had been a fixed maximum displacement for these kinematograms as there was for those of Braddick (1974), the maximum displacement would have followed a horizontal line across each graph.

The controls run with observer PC to examine any variation of equiluminance with element size show only moderate variation. It is not clear whether these are systematic

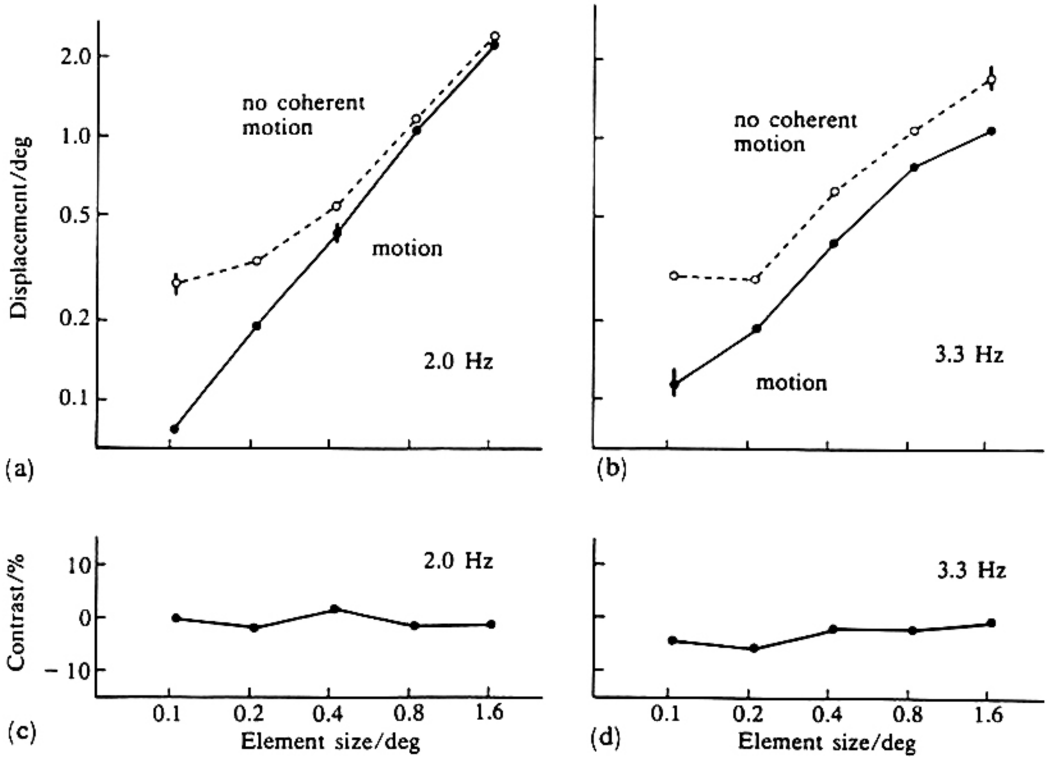

Figure 3. Panels (a) and (b) are as for figure 2. Panels (c) and (d) show equiluminance point as a function of element size at 2.0 Hz and 3.3 Hz, respectively. The contrast scale is as in figure 1. Observer PC.

trends or simply measurement error. In either case, on referring back to figure 1b, it is apparent that the variation seen here would not create significant changes in the observed maximum displacement.

4 Experiment 3: Alternation rate

Tyler (1973) has reported that the alternation rate influences the maximum displacement over which apparent motion can be seen. Specifically, the faster the alternation rate, the smaller the maximum displacement. In the third experiment we evaluated this relation for luminance (red/black) and chrominance (equiluminous red/green) kinematograms.

4.1 *Method*

This experiment was identical to experiment 2 except for two changes. First, element size was fixed at 0.42 deg. Second, five different alternation rates were tested (1.875, 3.75, 7.5, 15.0, and 30.0 Hz). The observers were again two of the authors (JB and PC) and a naive observer (CM).

4.2 *Results*

Maximum displacement at which coherent motion could be seen decreased with increasing cycle rate. Again, the luminance condition (red/black) had an advantage over the equiluminance condition (red/green) in terms of maximum observed displacement. There seemed to be no other significant differences between the two conditions (figure 4).

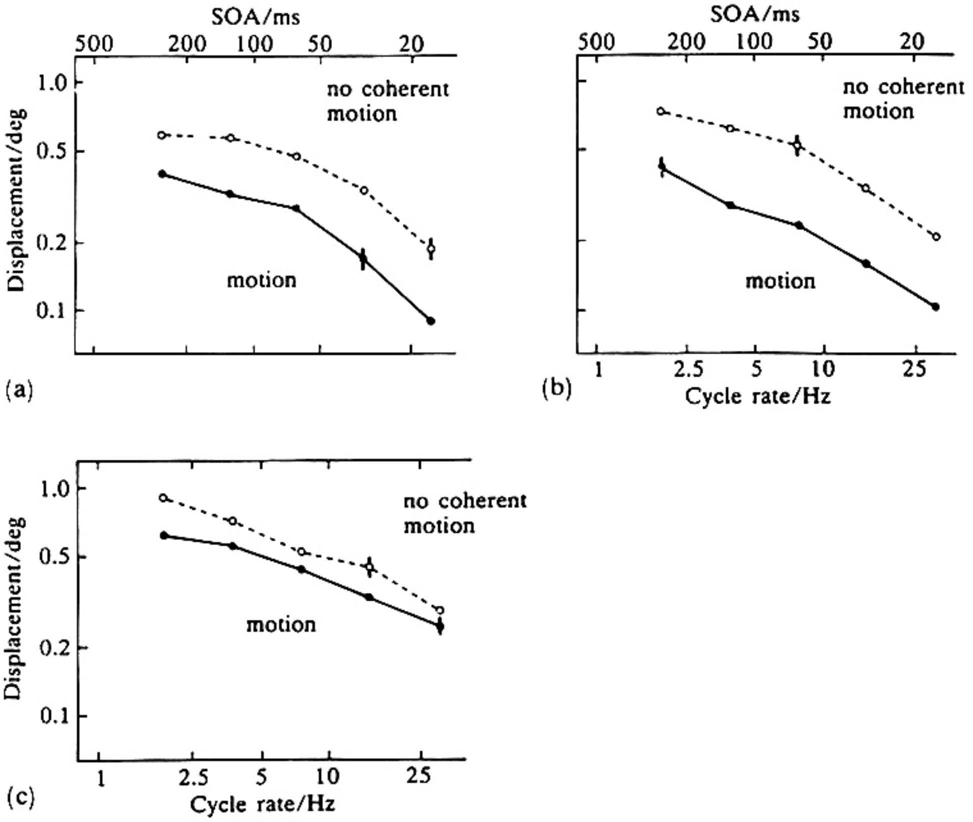

Figure 4. Maximum displacement at which coherent motion can still be seen as a function of cycle rate or stimulus onset asynchrony (SOA). Element size was fixed at 0.42 deg. Empty circles represent data for the luminance condition (red and black elements) and filled circles the equiluminance condition (red and green elements). Vertical bars show typical standard errors. (a) Observer PC; (b) observer JB; (c) observer CM.

5 Experiment 4: Apparent motion of equiluminous bar stimuli

Although Ramachandran and Gregory (1978) did not observe motion in equiluminous kinematograms, they did observe it in simple equiluminous line figures. Since we have observed motion in equiluminous kinematograms when ISI is effectively zero, we now examined the apparent motion of a simple equiluminous figure which was visible in each field in isolation. We measured the range of red/green contrast which gave no coherent motion first for a random-dot kinematogram with very large element size (0.85 and 1.70 deg) and then for a single isolated element of the same size moving through the same displacement. Four displacements and three alternation rates were evaluated for both stimulus types. The coherent motion criterion for the kinematograms was the same as in previous experiments. In the case of the single-bar element, the crossover from apparent motion to no motion was more obvious as the stimulus appeared to be simply blinking or flickering at the two bar positions.

5.1 *Method*

Four different stimuli were used: large or small red and green random dots (0.85 and 1.70 deg with an oscillating central square of 13.5 deg × 13.5 deg) and a narrow or wide green vertical bar (0.85 deg × 1.70 deg and 1.70 deg × 3.40 deg, respectively) viewed against a red background. Three different alternation rates of the central figure or bar were used (4.3, 3.3, and 2.7 Hz) and four different displacements. The displacement values were 0.21, 0.42, 0.63, and 0.85 deg for the small elements and 0.42, 0.85, 1.27, and 1.70 deg for the large elements. In both cases these displacements were equivalent to $\frac{1}{4}$, $\frac{1}{2}$, $\frac{3}{4}$, and 1 element widths. The display was identical in all other respects to that of experiment 1.

The experiment was composed of twelve blocks of trials (three alternation rates for large or small random dots or vertical bar). The observers were one of the authors (JB) and one naive subject (MG). The procedure was identical to that of experiment 1.

5.2 *Results*

The data in figure 5 show again that at zero ISI coherent motion can be seen in kinematograms at equiluminance. Both the dot size and the alternation rate affected the maximum displacement at equiluminance (the leftmost tip of the unshaded tongue) in the same manner as had been seen in experiments 2 and 3 (note that the displacement scale has been doubled for the element size of 1.70 deg). Larger element width produces larger maximum displacements, as does slower alternation rates. Maximum displacements equal to or greater than the element width were not achieved until alternation rate was slowed to 2.7 Hz.

Significantly, the data for the single-bar stimuli did not differ in any systematic way from those for the kinematograms. Thus, over the range of conditions that we have explored, we did not observe any qualitative difference between the two stimulus types at equiluminance. It should be noted that our conditions differed from the conditions of Ramachandran and Gregory (1978).

6 Discussion

Two separate processes appear to be involved in the perception of the central square seen in the kinematogram: motion and segregation. Our results show that the motion of the central area is visible with either luminance or chrominance contrast, although less so in the latter case. On the other hand, the segregation in depth of the central square from the static surround was visible only with luminance contrast. We shall discuss these two aspects in turn.

The loss of motion in equiluminous kinematograms reported by Ramachandran and Gregory (1978) and replicated by ourselves in experiment 1 (with 50 ms ISI) appears to

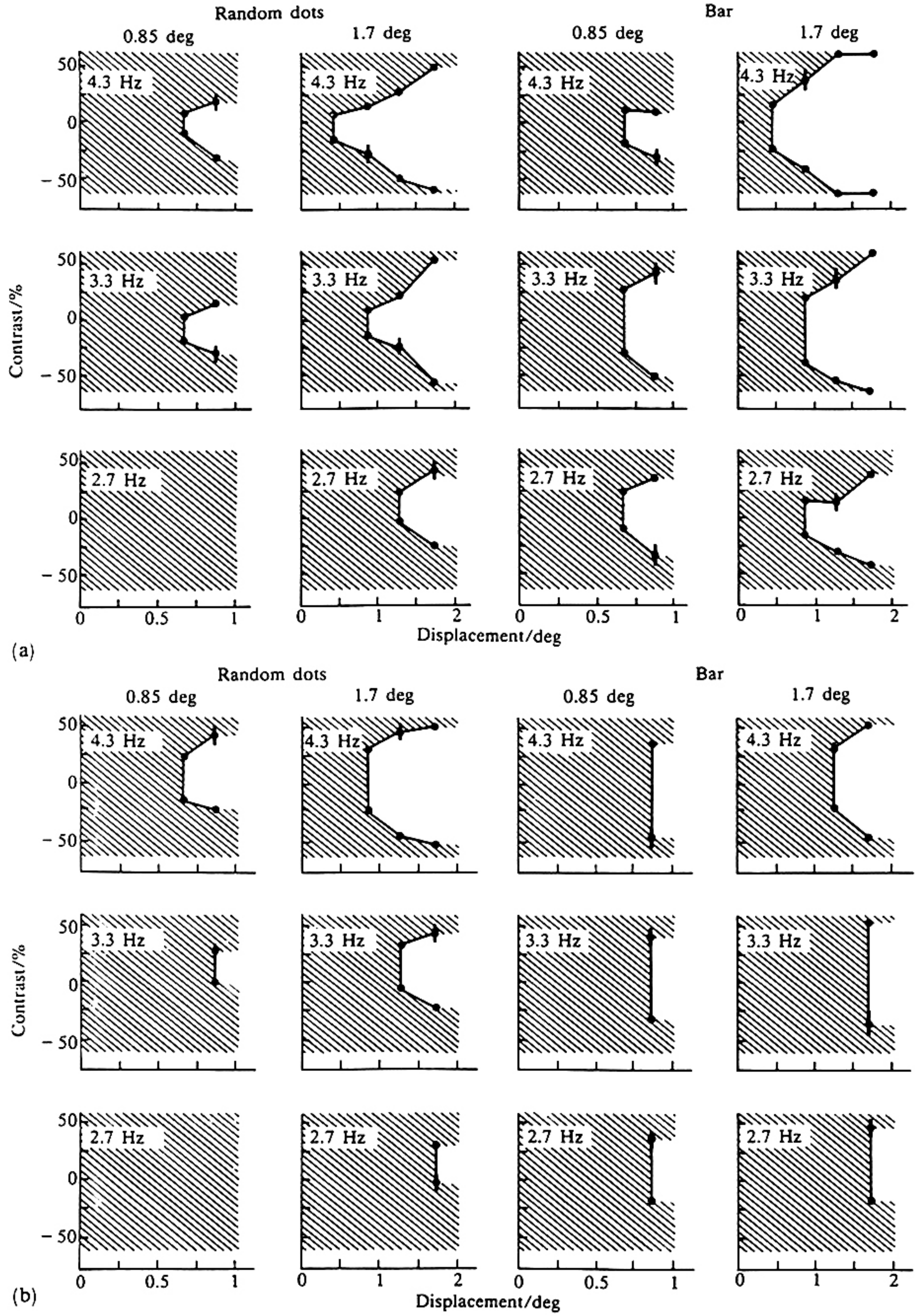

Figure 5. Red/green contrast ranges producing coherent-motion and no-motion reports as a function of alternation rate and displacement for random-dot kinematograms of 0.85 and 1.70 deg element size and for single bars of 0.85 and 1.70 deg width. The zero-contrast point is the present equiluminance value. Coherent motion is reported in the shaded areas while no motion is reported in the unshaded areas. Vertical bars show typical standard errors of the crossover points. The contrast scale is as in figure 1. (a) Observer MG; (b) observer JB.

be attributable to the interference of the dark ISI with motion perception (Braddick 1974; Lappin and Bell 1976). When no dark ISI is used, coherent motion is visible but the range of conditions over which motion is seen is restricted compared to that for kinematograms having luminance contrast. In particular, the maximum displacement over which motion can be seen approximately doubles when luminance contrast is present. The maximum displacement for equiluminous kinematograms appears to be about one element width at slower alternation rates (less at higher rates) and about two element widths when luminance contrast is present. Our finding that the maximum displacement is fixed in terms of element size is consistent with those of Chang and Julesz (1983a, 1983b) and Lappin and Bell (1976), and apparently contradicts those of Braddick (1974). However, Braddick varied element size from 0.045 to 0.170 deg, a range that only just overlaps ours, 0.11 to 1.70 deg. Within the overlapping region, our results for the luminance stimuli are in agreement with those of Braddick—a maximum displacement of about 0.2 deg—despite differences in overall display size and alternation rate. In fact, looking at figures 2 and 3, one finds that some flattening of the curve towards a lower asymptote of about 0.2 deg maximum displacement for element sizes smaller than 0.2 deg may be occurring. This would have to be verified in a further study but suggests that there may be an element size below which the motion system no longer resolves the individual dots but responds instead to clusters or blobs of dots still large enough to be resolved. Any further reduction in the element size cannot affect this smallest resolvable blob size except in terms of its contrast. (The grain of a low-pass-filtered random-dot field is unaffected by dot size once the dot sampling frequency is above the filter cutoff frequency.) The maximum displacement would therefore remain constant below this element size.

Braddick's (1974) 15 min displacement limit and our one-element or two-element displacement limit may therefore both be the result of a single motion process and its lower resolution limit. In our data, the same motion process appears to be responsible for perceiving kinematograms over a four octave range in element size for our study and over displacements in excess of 2 deg in some instances. Indeed, our final experiment revealed no difference between the conditions required to perceive coherent motion in the random-dot kinematogram and those required for an isolated bar. No aspects of our data appear to require the assumption of separate long-range and short-range motion processes.

The displacements examined in our experiments ranged from zero to several element widths in steps of ¼ of an element width. A true kinematogram requires a displacement of an integral number of elements for the displaced area to be invisible in each independent field, as a fractional displacement leaves a column of partial elements at each edge of the form. It could be argued that these cues make the identification of the motion a simpler task. However, we do not observe any advantage of fractional over integral displacements in our data (eg coherent motion lost over narrower ranges of contrast around equiluminance for fractional displacements in figures 1 and 5). This suggests that no special process is involved in solving the correspondence problem for integral displacements as compared to partial displacements.

The observation of motion at equiluminance implies that there is conjoint analysis of colour and motion in the visual system as is suggested by colour-contingent motion aftereffects (Lovegrove et al 1972; Mayhew and Anstis 1972; Favreau et al 1972; Favreau 1976) and by physiological recordings (Michael 1978). Even though motion can be seen at equiluminance in the kinematogram, the segregation of the central square from the background is lost as had been reported by Ramachandran and Gregory (1978). This loss of segmentation was not studied quantitatively here, but all subjects reported that the impression of depth (the oscillating square in front of the background) and the sharply defined edges disappear dramatically at equiluminance. The absence of segregation at equiluminance suggests that colour may not feed into figural segmentation processes. Specifically, processes that rely on relative motion to deduce depth or segmentation of figure from ground appear to require some luminance contrast.

It is important to examine to what extent equiluminance was achieved in the experiments here. Even though the red/green luminance ratio was varied over a continuous range that necessarily included the minimum luminance difference, that minimum was not necessarily zero. In particular, edges may produce irreducible luminance artifacts due to chromatic aberration in the eye or to colour misalignment or poor temporal response of the display. We observed the display at equiluminance both with and without an achromatizing lens and found no noticeable difference in the motion. This is not unexpected as the red and green available in TV monitors do not produce a large degree of chromatic aberration. In addition, we ran a control condition in which observers sat at five different viewing distances (35, 52, 70, 105, and 140 cm). The kinematogram always subtended the same visual angle (its size on the display screen was decreased as the observer moved closer). The displacement of the central square was just enough ($1\frac{1}{4}$ element widths) to create a small no-motion region around equiluminance at the 140 cm viewing distance. If edge artifacts were carrying the motion at equiluminance, they should be four times more effective at a viewing distance of 35 cm than at 140 cm. No effect of viewing distance on the no-motion range was found however. We conclude that edge artifacts in the display are not responsible for the motion perceived at equiluminance.

Other recent work (Anstis and Cavanagh 1983) has shown that equiluminance varies with spatial frequency. The kinematogram, with its randomly located abrupt edges, contains a broad range of spatial frequencies. Conceivably, it may be impossible to obtain equiluminance simultaneously for all of these spatial-frequency components. If it is theoretically impossible to obtain a truly equiluminous kinematogram, then other stimuli may be more appropriate for studying motion with equiluminous stimuli. We have reported recently (Cavanagh et al 1984) on the perception of motion in drifting, equiluminous sine-wave gratings. Our observations there, as here, show that equiluminous displays do provide a stimulus for motion, although a weak one.

In summary, our data do not require the assumption of two separate motion processes, long range and short range, but they do suggest separate motion and segregation processes: the first sensitive to both colour and luminance, although less so to colour, and the second sensitive only to luminance.

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