

Lightness differences and the perceived segregation of regions and populations

JACOB BECK

University of Oregon, Eugene, Oregon

NORMA GRAHAM

Columbia University, New York, New York

and

ANNE SUTTER

University of Oregon, Eugene, Oregon

A striking finding reported by Beck, Sutter, and Ivry (1987) was that, in textures composed of regions differentiated by the arrangement (checks and stripes) of two texture elements (light and dark squares), a large lightness difference between the squares could fail to yield segregation between the regions, whereas a smaller lightness difference could sometimes yield strong segregation. In the experiments reported here, we compared the segregation of striped and checked arrangements of light and dark squares into regions with the segregation of two randomly interspersed populations of light and dark squares into subpopulations. Perceived lightnesses are the same for a given set of squares, whether they are arranged in regions or in intermixed populations. Perceived population segregation is approximately a single-valued function of the lightness differences of the squares, but perceived region segregation is not. The reason for the difference between population segregation and region segregation may be that region segregation is mediated by detectors' having large oriented receptive fields (large bar detectors) that are sensitive to the fundamental spatial frequency and orientation of the texture region as defined by the arrangement of the squares (Beck et al., 1987; Sutter, Beck, & Graham, 1989). These detectors cannot be responsible for population segregation, because the light and dark squares are distributed randomly throughout these patterns and therefore do not define a consistent arrangement of any particular spatial frequency or orientation. The light and dark squares in the population patterns fall equally on excitatory and inhibitory regions of large bar detectors. A plausible explanation for population segregation is to suppose that the segregation is the result of similarity grouping of the light and dark squares.

Much effort has been expended over the last 25 years in attempts to specify precisely what information leads to the immediate and effortless segregation of a visual pattern (for reviews, see Beck, 1982; Beck, Prazdny, & Rosenfeld, 1983; Bergen, in press). In the experiments reported here, we examined the role of differences between the lightnesses of pattern elements. Beck, Sutter, and Ivry (1987) investigated region segregation in three-part patterns in which each part contained approximately equal numbers of two different elements on a background of uniform luminance (e.g., the light and dark squares on the white background in Figure 1). The regions to be segregated differed in the arrangement of the squares. In the top and bottom regions, the squares were arranged in vertical stripes. In the center region, the squares were arranged in a checked pattern. A striking observation reported by

Beck et al. (1987) was that squares differing greatly in lightness sometimes failed to give region segregation, but that the same pattern of squares differing by a smaller lightness difference could yield strong region segregation.

In that experiment, the lightness judgments were made only informally by the experimenters. However, the following argument could be made to suggest further that the strength of region segregation was not a single-valued function of the lightness differences of the squares. When the luminance of a background is greater than the luminance of a surface, the lightness of the surface is determined by the ratio of the surface luminance to the background luminance or to the average luminance of its background (Arend & Goldstein, 1987; Flock, 1970, 1971; Flock & Noguchi, 1970; Gilchrist & Jacobson, 1989; Heinemann, 1989; Helson, 1964; Jacobson & Gilchrist, 1988). Further, perceived lightness may be taken to be, to a first approximation, a logarithmic function of the relative luminance of the surface to its background (Judd & Wyszecki, 1963). To the extent that this approximation holds, then, when the background luminance is the same,

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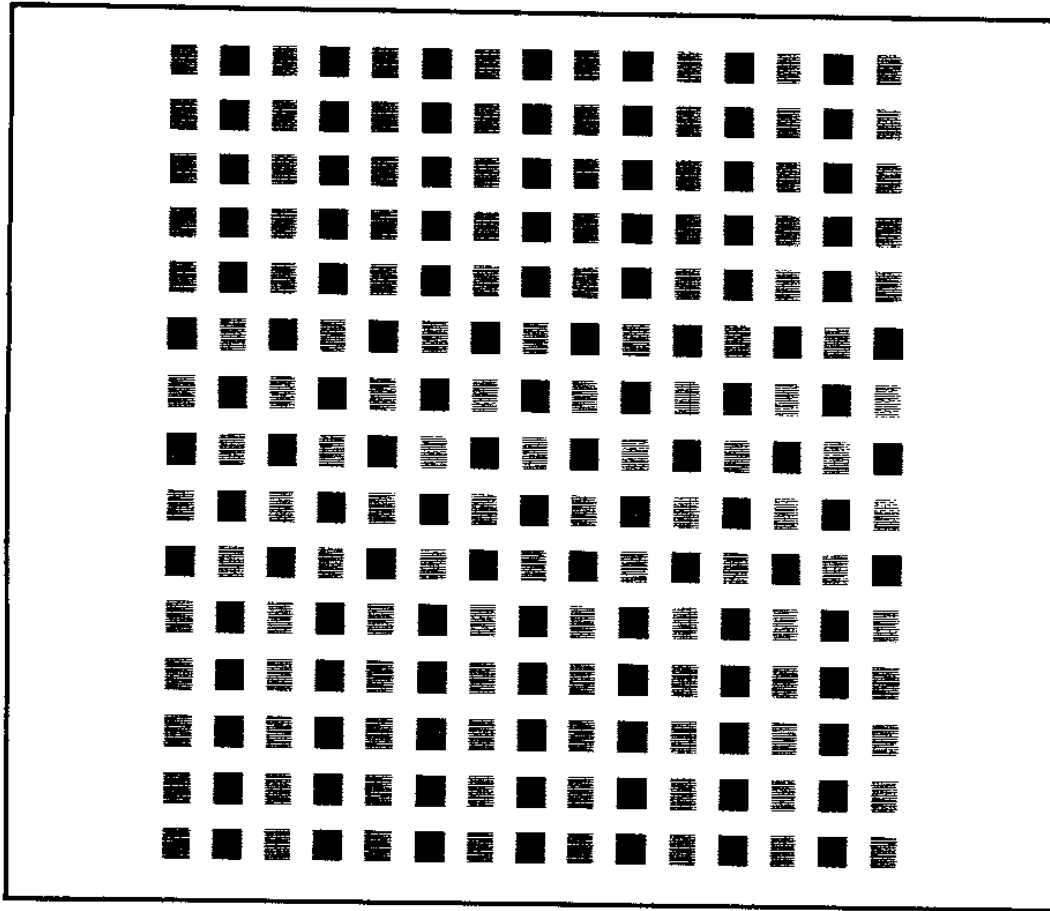


Figure 1. An example of the tripartite patterns investigated in Experiments 1 and 2.

the difference in lightness of the light and dark squares will be given by the equation

$$Y_1 - Y_2 = k \log \frac{L_1}{L_2}, \quad (1)$$

where Y_i is lightness, and L_i is the luminance of a square. In Figure 2, we replot the data from Beck et al. (1987). The squares were on a white (high-luminance) background. In Figure 2 (top), perceived region segregation is plotted as a function of the ratio of the luminances of the lighter and darker squares. Perceived region segregation is not a single-valued function of the ratio of their luminances. For example, when the ratio of the background luminance to that of the light square was 1.2, perceived segregation improved greatly with increasing luminance ratios of the light to dark squares (filled circles). When the ratio of the background luminance to the luminance of the light square was 2.0, perceived segregation

was poor even when the luminance ratio of the lighter to darker squares was very large (unfilled triangles). Since it is the ratio of the luminances of the lighter to darker squares that to a first approximation determines their lightness difference, the diverse curves in Figure 2 (top) suggest that region segregation is not a simple function of the lightness difference between the squares. In Figure 2 (bottom), perceived region segregation is plotted as a function of the ratio of the contrasts of the dark (high-contrast) and light (low-contrast) squares.¹ Clearly, perceived region segregation is well described by a monotonic, negatively accelerated, single-valued function of contrast ratio.

EXPERIMENTS

Region Segregation versus Population Segregation

In four experiments, we investigated the relation of region segregation and population segregation to lightness

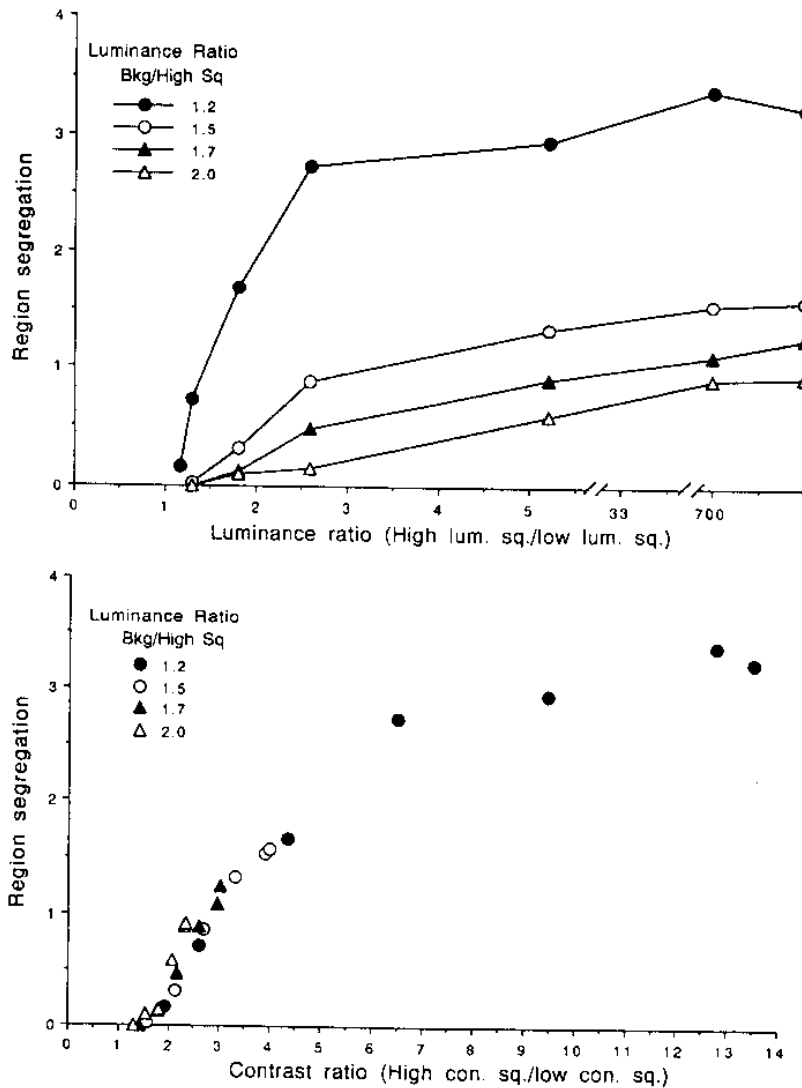


Figure 2. Mean segregation ratings in Beck, Sutter, and Ivry (1987). The top graph shows the ratings as a function of the ratio of the luminances of the light and dark squares. The bottom graph shows the same data as a function of the ratio of their contrasts.

differences. *Region segregation* refers to the segregation of a pattern into separate spatial regions. *Population segregation* refers to the segregation of a pattern into two interspersed subpopulations. These two subpopulations do not define separate spatial regions, but rather are randomly distributed throughout the pattern. The subjects both rated the perceived segregation of a pattern and matched the lightnesses of the light and dark squares in a pattern to a lightness scale. In Experiments 1 and 2, the light and dark squares were arranged in 15 rows and 15 columns

(Figure 1). The subjects rated the perceived segregation of a stimulus into three regions. In Experiments 3 and 4, the light and dark squares were randomly distributed throughout the pattern (Figure 8). The subjects rated the perceived segregation of a stimulus into two subpopulations.

General Method

Stimuli and Apparatus

The stimuli were generated by a Symbolics 3600 Lisp machine. In Experiment 1, the stimuli were pictures of the computer-generated

images printed on a Tektronix 4634 hardcopy unit. In Experiments 2, 3, and 4, the stimuli were presented on a Tektronix 690 SR RGB monitor. Subjects viewed the stimuli from a distance of 3.5 ft in Experiment 1 and from a distance of 6.0 ft in Experiments 2, 3, and 4. The squares were 0.2 in. on a side in Experiment 1 and 0.36 in. (16 pixels) on a side in Experiment 2. A square subtended 16' of arc in Experiment 1 and 17.28' of arc in Experiments 2, 3, and 4 (1 pixel = 1.08' on the RGB monitor). The center-to-center distances of the squares were 0.26 in. in Experiment 1 and 0.63 in. (28 pixels) in Experiment 2. In Experiments 3 and 4, the squares were randomly distributed throughout the pattern and the center-to-center distances of the squares varied. Luminances, measured with a Spectra-Pritchard spot meter, are reported below in the sections on the individual experiments.

Segregation Ratings

As described further below, there were 15 stimuli in Experiment 1 and 25 in Experiments 2, 3, and 4. A block of trials consisted of 1 presentation of each stimulus, with the order randomized. Each subject made segregation ratings of 3 blocks of stimuli. In Experiments 1 and 2, the subjects were asked to rate on a 5-point scale from 0 to 4 the distinctness of the three regions in a pattern. They were instructed not to scrutinize the patterns to find the boundaries between the three regions, but rather to base their judgments on their first impressions. In Experiments 3 and 4, they were asked to rate the segregation of the two intermixed populations on a scale from 0 to 4. A rating of 4 indicated that the regions in Experiments 1 and 2 or the subpopulations in Experiments 3 and 4 segregated strongly. A rating of 0 indicated that the regions or subpopulations in a pattern did not segregate at all; that is, they appeared to constitute a single pattern. The subjects were explicitly instructed to judge not the discriminability of the individual light and dark squares but how well the patterns as a whole segregated into regions or populations. The means of individual subjects' mean segregation ratings are plotted in the graphs. In all four experiments, the subjects were shown sample stimuli to familiarize them with the range of stimulus variations, and they were given practice trials.

In Experiment 1, the stimuli were placed by the experimenter on a stand. The exposure duration was not controlled. Each stimulus was removed as soon as the subject made a judgment. The subjects made their judgments readily and quickly. In Experiments 2, 3, and 4, the subjects initiated each experimental trial by pressing a mouse button situated on a desk in front of them. An experimental trial consisted of the following sequence: A blue fixation X was presented for one second in the center of a blank screen; immediately after the offset of the fixation X, the stimulus appeared and remained on the screen for 1 sec, after which it disappeared and the screen was blank. Throughout an experiment, including the intervals during which the screen was blank, the background luminance of the screen remained constant at the value of the background for the stimuli in that experiment. After the stimulus disappeared from the screen, the subjects recorded their rating on a rating sheet and pressed the mouse button to initiate the next trial.

Lightness Matches

After the three blocks of stimuli on which subjects made segregation ratings, two more blocks of stimuli were presented, during which the subjects matched the lightnesses of the light and dark squares in a pattern. The subjects were asked to match the lightness of two squares from the center region in a pattern to a gray scale. In Experiment 1, the gray scale was a 32-step Munsell chart ranging from a Munsell value of 9.5 to a Munsell value of 1.75 in .25 steps. The chart was held in the subject's hand. In Experiments 2, 3, and 4, the scale appeared on the CRT to the right of the texture pattern. It contained 10 gray levels from white to black; these were numbered from 1 to 10, and they appeared against a

gray background (9.96 fL). The luminances of the comparison rectangles were 0, 0.70, 1.56, 2.64, 6.06, 8.22, 9.96, 14.40, 20.25, and 31.6 fL. Munsell matches to these 10 comparison rectangles were made by 3 observers, who used a 10-step Munsell scale ranging from a Munsell value of 9.5 to a Munsell value of 1.0. The mean matches were Munsell values of 1.75, 2.75, 3.75, 4.58, 6.33, 7.50, 8.17, 8.75, 9.0, and 9.50. The gray scale was displaced by approximately 2° (110 pixels) from the right edge of a stimulus pattern. Practice in making lightness matches was given before presentation of the two blocks of stimuli.

The subjects were encouraged to use decimal values if the lightness of a square appeared to lie between two gray scale values. The subjects could look alternately at a stimulus pattern and the gray scale comparison chart. In Experiments 2, 3, and 4, depressing the left mouse button displayed a stimulus, and depressing the right mouse button displayed the comparison lightness chart. The subjects recorded their lightness matches on a rating sheet and depressed the middle mouse button to initiate the next trial. In all four experiments, the subjects were given as much time as they needed to match the lightnesses of the squares to the gray values on the comparison chart. For each subject, the lightness difference between the lighter and darker squares composing a stimulus was computed from the mean lightness matches made by the subject with the lighter and darker squares. The graphs plot the mean of individual subjects' lightness differences.

Subjects

Ten different subjects served in each experiment. All subjects had normal or corrected-to-normal vision and were paid for their participation. The subjects were naive concerning the purposes of the experiments.

EXPERIMENT 1 Region Segregation: White Background

Our aim in Experiment 1 was to investigate whether region segregation in the tripartite pattern is a single-valued function of the lightness differences or of the contrast ratios of the lighter and darker squares. The lighter and darker squares were on a white (higher luminance) background.

Stimuli

Fifteen stimuli were presented. The background luminance was 38.0 fL. For five stimuli, the light square was 35.0 fL, and the darker square was 32.0, 31.0, 27.0, 23.5, or 19.5 fL, respectively. For six stimuli, the lighter square was 27.0 fL, and the darker square was 19.5, 15.5, 11.5, 10.0, 6.0, or 3.5 fL, respectively. For two stimuli, the lighter square was 23.5 fL, and the darker square was 6.0 or 3.5 fL, respectively. For two stimuli, the lighter square was 19.5 fL and the darker square was 6.0 or 3.0 fL, respectively. The ratios of the background luminance to the luminances of the lighter square were 1.09, 1.41, 1.62, and 1.95, respectively.

Results

Region segregation. Figure 3 shows perceived region segregation as a function of the lightness difference calculated from subjects' lightness matches of the light and dark squares. There is no simple functional relationship between perceived region segregation and the magnitude of the lightness difference. As in Beck et al. (1987), equal lightness differences lead to different perceived region segregations, depending on the relationship of the background luminance to the luminance of the light square. For example, when the ratio of the background luminance to the

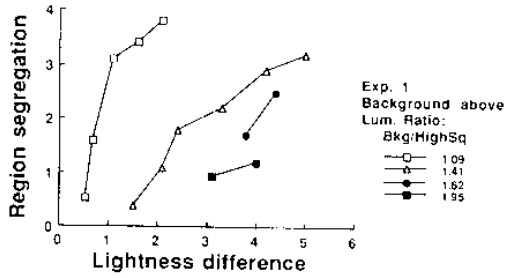


Figure 3. Mean segregation ratings as a function of the mean of the differences in subjects' lightness matches in Experiment 1.

luminance of the light square was 1.09 (unfilled square), good region segregation occurred with Munsell lightness differences of between 1 and 2 steps. When the ratio of the background luminance to the luminance of the light square was 1.95 (filled square), region segregation failed to occur with Munsell lightness differences of 3 and 4 steps.

Perceived region segregation plotted as a function of the logarithm of the ratio of the luminances of the light and dark squares is shown in Figure 4a. Perceived segregation is not a single-valued function of the luminance

ratios of the light and dark squares. When the ratio of the background luminance to the luminance of the light square was 1.09 (unfilled squares), perceived region segregation increased dramatically as a function of the luminance ratio of the light and dark squares. When the ratio of the luminance of the background to the light square was 1.95 (filled squares), perceived region segregation remained weak with much larger luminance ratios of the light and dark squares. Perceived segregation as a function of the ratio of the contrasts of the light and dark squares is shown in Figure 4b.² Perceived region segregation is approximately a single-valued function of the ratio of the contrasts of the light and dark squares.

Lightness differences. The differences between subjects' lightness matches of the light and dark squares plotted as a function of the logarithm of the ratio of their luminances is shown in Figure 4c and as a function of the ratio of their contrasts in Figure 4d. Lightness differences are well described as a single-valued function of the ratio of the luminances of the light and dark squares (Figure 4c) but not of their contrasts (Figure 4d). Indeed, plotting the lightness difference versus the logarithm of the luminance ratio yields a good approximation to a straight line as predicted by Equation 1, although there is a little curvature.

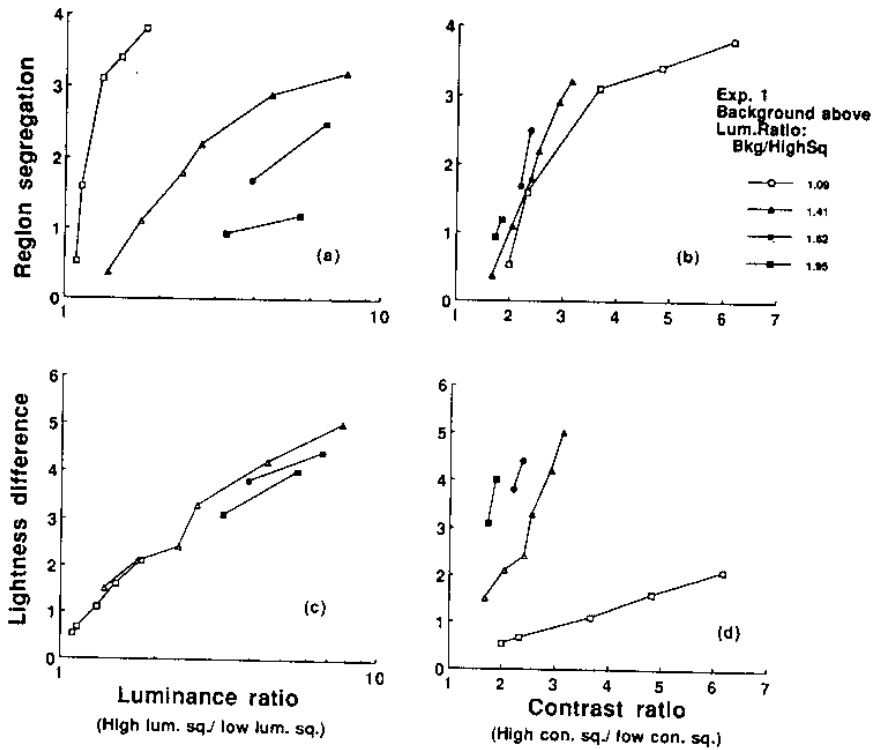


Figure 4. Mean segregation ratings and the mean of the differences in subjects' lightness matches as a function of the logarithm of the ratio of the luminances of the light and dark squares and as a function of the ratio of their contrasts in Experiment 1.

EXPERIMENT 2
Region Segregation:
White, Gray, and Black Backgrounds

In Experiment 2, we investigated the effects of varying the background luminance on region segregation. The light and dark squares composing a stimulus were presented on white, gray, and black backgrounds. On the white background, both squares were darker; on a black background, both squares were lighter, and on a gray background, the lightness of the background was between that of the squares.

Stimuli

Twenty-five stimuli were presented: 10 with a black background, 10 with a white background, and 5 with a gray background. Table 1 shows the background luminance, the luminance of the lower contrast square, the luminance of the higher contrast square, the luminance ratio, and the contrast ratio of the 25 stimuli. With a black (0.99-fL) background, the luminance of the darker (lower contrast, lower luminance) squares was fixed for five of the stimuli at 1.1 fL (Stimuli 1-5 in Table 1) and for the other five stimuli at 4.1 fL (Stimuli 6-10). Thus the ratio of the luminance of the darker square to the background luminance was 1.1 or 4.04. With a white (40.0-fL) background, the luminance of the lighter (lower contrast, higher luminance) square was fixed for five of the stimuli at 33.2 fL (Stimuli 11-15) and for the other five of the stimuli at 12.0 fL (Stimuli 16-20). Thus the ratio of the background luminance to the luminance of the lighter square was 1.2 or 3.3. With a gray (9.96-fL) background, the two squares were of equal contrast and set above and below the luminance of the gray background by approximately equal amounts (Stimuli 21-25).

Results

Region segregation. Figure 5 (top) shows perceived region segregation as a function of the lightness difference calculated from subjects' lightness matches of the lighter and darker squares in a pattern. As in Experiment 1, equal lightness differences lead to different region segregation judgments, depending on the relationship of the background luminance to the square luminances. For example, when the background was white, perceived segregation increased steeply with lightness differences when the luminance ratio of the background to the lighter square was 1.2 (filled squares). When the ratio of the background luminance to the lighter square was 3.3 (unfilled squares), strong texture segregation failed to occur with lightness differences of 3 and 4 steps. When the background was black, perceived segregation increased steeply with lightness differences when the luminance ratio of the darker square to the background was 1.1 (filled circles). When the luminance ratio of the darker square to the background was 4.1 (unfilled circles), strong perceived segregation again failed to occur with lightness differences of 3 and 4 steps. When the background luminance was between that of the squares (filled triangles), perceived region segregation was strong. Perceived segregation was similar to that occurring with the background below and a luminance ratio of the darker square to the background of 1.1 (filled circles).

In Figure 6a, perceived region segregation is plotted as a function of the logarithm of the ratio of the luminances of the lighter (high-luminance) and darker (low-luminance) squares. No single curve relates perceived

Table 1
 Stimulus Luminances in Experiments 2, 3, and 4 (in Foot-Lamberts)

Stimulus	Background	Lower Contrast Square	Higher Contrast Square	Luminance Ratio	Contrast Ratio
1	0.99	1.10	1.10	1.00	1.00
2	0.99	1.10	1.20	1.09	1.91
3	0.99	1.10	1.25	1.14	2.36
4	0.99	1.10	1.35	1.23	3.27
5	0.99	1.10	1.49	1.35	4.55
6	0.99	4.04	4.04	1.00	1.00
7	0.99	4.04	5.00	1.24	1.32
8	0.99	4.04	6.06	1.50	1.66
9	0.99	4.04	8.06	2.00	2.32
10	0.99	4.04	11.10	2.75	3.32
11	40.00	33.20	33.20	1.00	1.00
12	40.00	33.20	31.20	1.06	1.29
13	40.00	33.20	29.20	1.14	1.59
14	40.00	33.20	26.00	1.28	2.06
15	40.00	33.20	18.75	1.77	3.13
16	40.00	12.00	12.00	1.00	1.00
17	40.00	12.00	8.70	1.38	1.12
18	40.00	12.00	5.70	2.11	1.23
19	40.00	12.00	3.80	3.16	1.29
20	40.00	12.00	0.10	120.00	1.43
21	9.96	10.50	9.42	1.12	-1.00
22	9.96	10.90	9.06	1.20	-0.96
23	9.96	11.50	8.36	1.38	-1.04
24	9.96	15.00	5.00	3.00	-0.98
25	9.96	19.95	0.10	199.50	-0.99

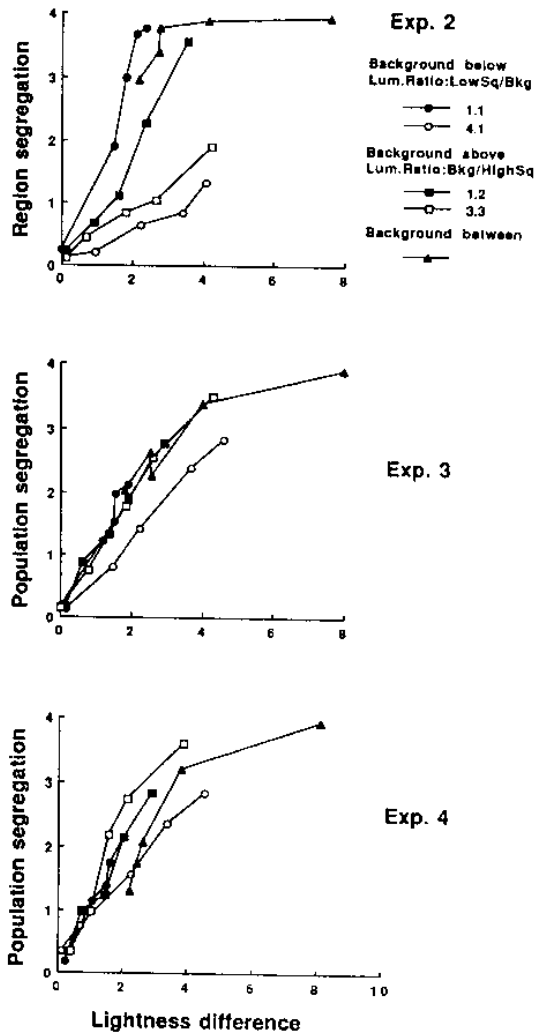


Figure 5. Mean segregation ratings as a function of the mean of the differences in subjects' lightness matches in Experiments 2, 3, and 4.

region segregation to the luminance ratios of the lighter and darker squares. The results with a white background are as those in Experiment 1. For example, when the ratio of background luminance to the lighter square was relatively small (filled squares), perceived region segregation increased sharply as a function of the luminance ratio of the lighter and darker squares. When the ratio of background luminance to the lighter square was relatively large (unfilled squares), perceived region segregation remained weak with much larger luminance ratios of the lighter and darker squares. The results with a black background are like those with a white background. When the ratio of the darker square to the background luminance was relatively small (filled circles), perceived region segregation in-

creased steeply with increases in the luminance ratios of the lighter and darker squares. When the ratio of the darker square to the background luminance was relatively large (unfilled circles), perceived region segregation remained weak with large luminance ratios of the lighter and darker squares. As in Beck et al. (1987), perceived segregation was strong when the background luminance was between the luminances of the squares (a gray background), and it decreased only when the luminance ratios of the light to the dark squares were 1.1 and 1.2 (filled triangles).

In Figure 7a, perceived region segregation is plotted as a function of the ratio of the contrasts of the light and dark squares. (The condition in which the background luminance was between that of the two squares is not plotted in Figure 7, since it would always plot at -1.0). In Experiment 1, perceived region segregation tended to be a monotonic function of the contrast ratio of the lighter and darker squares. Here the results tend to cluster around a single function, except when the square's luminances are far from the background luminance (the open squares and the open circles in Figure 7a). These divergences from a single function may reflect light-adaptation processes. The output from early sensory processes may be a compressive function of luminance, and the input to the channels responsible for region segregation may be the output from this compressive nonlinearity rather than luminance. This may account both for why, when the background luminance is dark and both squares' luminances are far above it (open circles), perceived segregation grows rather slowly with increasing contrast ratio (and thus with increasing luminance of the variable, lighter square), and also for why, when the background is light and both squares' luminances are far below it (open squares), perceived segregation grows rather quickly with increasing contrast ratio (and thus with decreasing luminances of the variable, darker square).

Lightness differences. As in Experiment 1 and in Beck et al. (1987), Figure 6b shows that the difference between the lightness matches was a single-valued function of the logarithm of the ratio of the luminances of the squares, except when the background was white and the luminance ratio of the background to the darker square was relatively large (unfilled squares). In this condition, the lightness differences increased more slowly as a function of the ratio of the luminances of the lighter and darker squares. This occurred also in Experiments 3 and 4 and will be discussed later.

EXPERIMENTS 3 AND 4 Population Segregation: White, Gray, and Black Backgrounds

In Experiments 3 and 4, we studied the segregation of a display into two populations as a function of the lightness differences of the light and dark squares. The arrangement of the light and dark squares did not define two distinct spatial regions but were randomly distributed throughout the pattern (Figure 8).

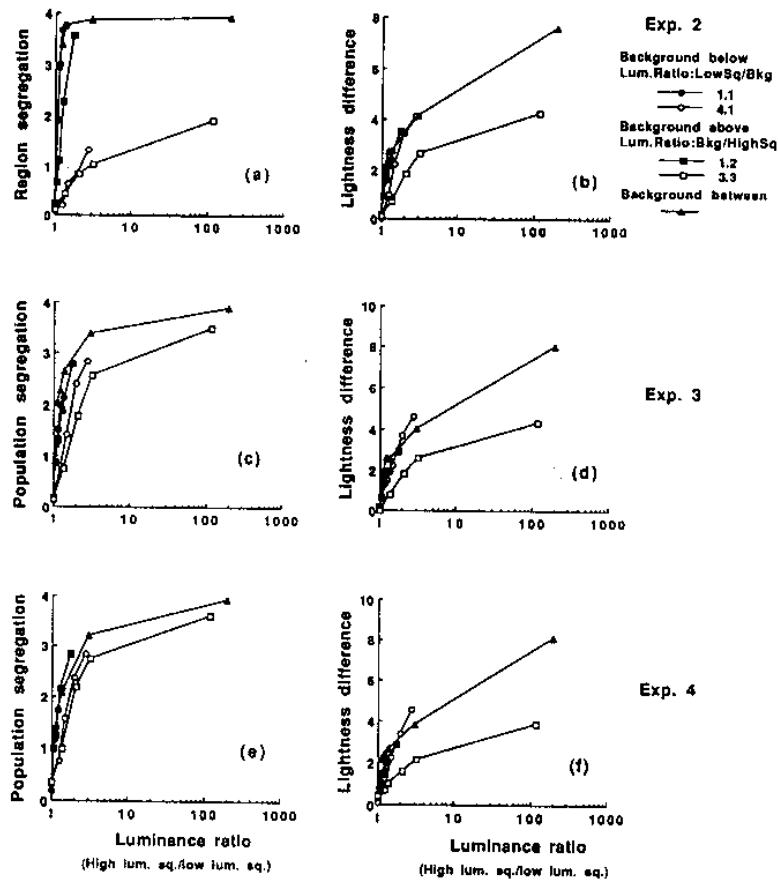


Figure 6. Mean segregation ratings and the mean of the differences in subjects' lightness matches as a function of the logarithm of the ratio of the luminances of the light and dark squares in Experiments 2, 3, and 4.

Stimuli

The sizes of the squares and the luminances of the squares and of the backgrounds in Experiments 3 and 4 were the same as in Experiment 2. Figures 8a and 8b show the arrangements of the squares in Experiments 3 (top) and 4 (bottom), respectively. In Experiment 3, a stimulus consisted of 32 light squares and 24 dark squares. The displays in Experiments 3 and 4 were 300×350 pixels. The density of squares in Experiment 3 was much less than it was in Experiment 2. In Experiment 4, the density of squares was made more similar to that in Experiment 2. The number of light squares was 41 and the number of dark squares 40.

Results

Population segregation. Perceived population segregation as a function of the lightness difference of the squares is shown in Figure 5 (middle) for Experiment 3 and in Figure 5 (bottom) for Experiment 4. A comparison of the middle and bottom panels of Figure 5 with the top panel of Figure 5 and with Figure 3 shows that the scatter of population segregation judgments is much less in Experiments 3 and 4 than the scatter of the region segregation judgments

in Experiments 2 and 1. These plots were fitted with the best-fitting curve from a general family of monotonic functions (see the Appendix for details). The proportions of the variance in perceived population segregation accounted for by the lightness differences in Experiments 3 and 4 were .92 and .88, respectively. The proportions of the variance in perceived region segregation accounted for in Experiments 2 and 1 were .48 and .07. Lightness differences predicted perceived segregation much better in Experiments 3 and 4 than in Experiments 2 and 1.

It is clear, however, that the population segregation ratings in Experiments 3 and 4 were not determined solely by the lightness differences. Systematic deviation from a single function can be seen in the middle and bottom panels of Figure 5. For example, perceived population segregation as a function of lightness difference was greater in both Experiments 3 and 4 when the background was white and the ratio of the luminance of the background to the luminance of the light square was 3.3 (unfilled squares) than it was when the background was black and

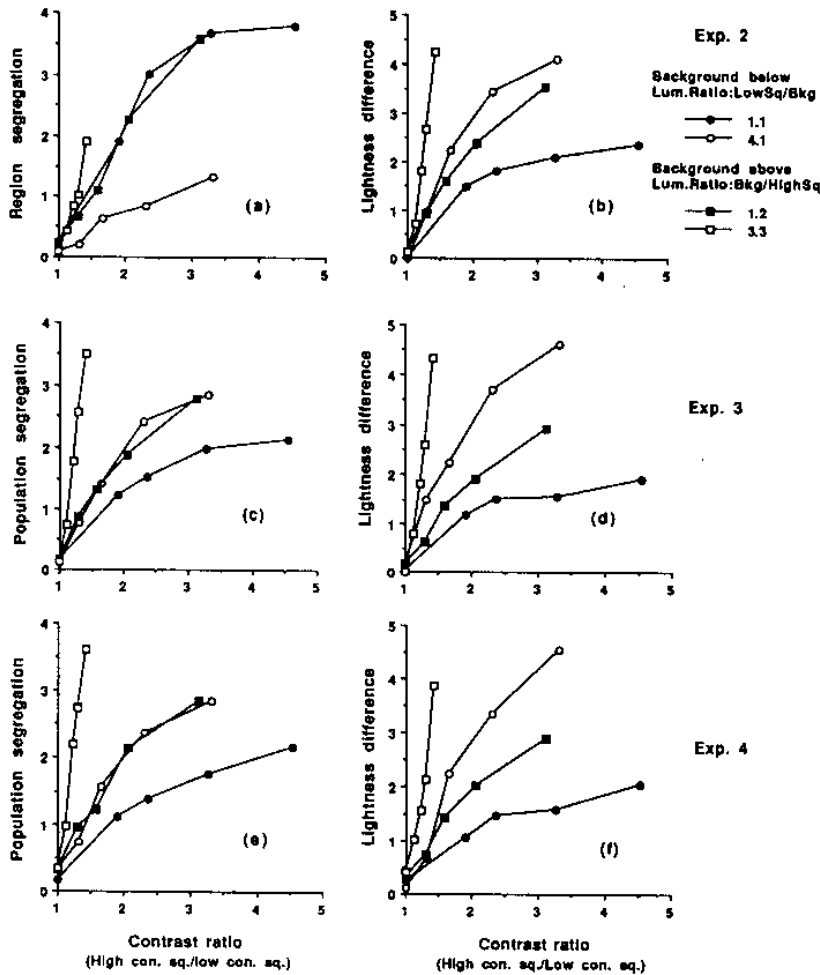


Figure 7. Mean segregation ratings and the mean of the differences in subjects' lightness matches as a function of the ratio of the contrasts of the light and dark squares in Experiments 2, 3, and 4. The condition in which the background luminance was between that of the two squares is not plotted, since it would always plot at -1.

the ratio of the luminance of the dark square to the luminance of the background was 4.1 (unfilled circles).

Perceived population segregation ratings were highly similar in Experiments 3 and 4, but they differed from the perceived segregation ratings in Experiment 2. In Figure 9 (top), the segregation values in Experiment 4 are plotted against those in Experiment 3 for the same luminances of squares and backgrounds. The r^2 value between the segregation judgments in Experiments 3 and 4 is .94 (either fit linearly or nonlinearly; see the Appendix). In the middle and bottom panels of Figure 9, the population segregation values in Experiments 3 and 4 are plotted against the region segregation values in Experiment 2. They show considerable scatter. The r^2 values for a non-

linear monotonic fit (see the Appendix) between Experiments 2 and 3 and between Experiments 2 and 4 ranged between .56 and .66 and between .42 and .50, respectively.

The population segregation judgments in Experiments 3 and 4 as a function of the logarithm of the luminance ratio of the squares (Figures 6c and 6e) show less scatter than do the region segregation judgments in Experiments 1 and 2, but, as a function of contrast ratio (Figures 7c and 7e), they show more scatter. A comparison of the results in Figure 5 and in the left panels of Figure 6 (when the abscissa in Figure 6 is made linear rather than logarithmic) suggests that in Experiments 3 and 4 perceived population segregation is more nearly a single-valued function of lightness differences than of luminance ratios. This indicates that

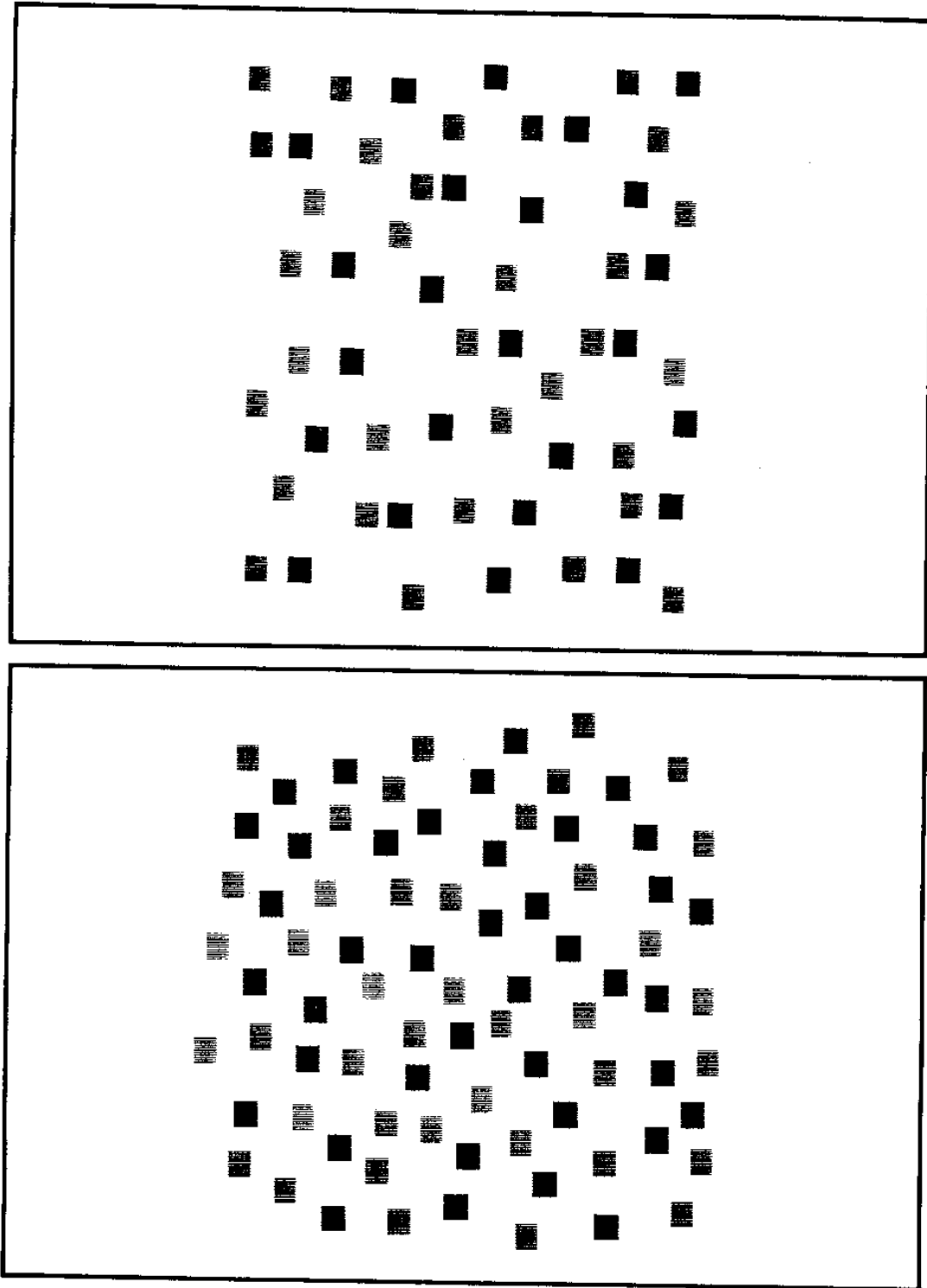


Figure 8. An example of the population stimuli investigated in Experiment 3 (top) and in Experiment 4 (bottom).

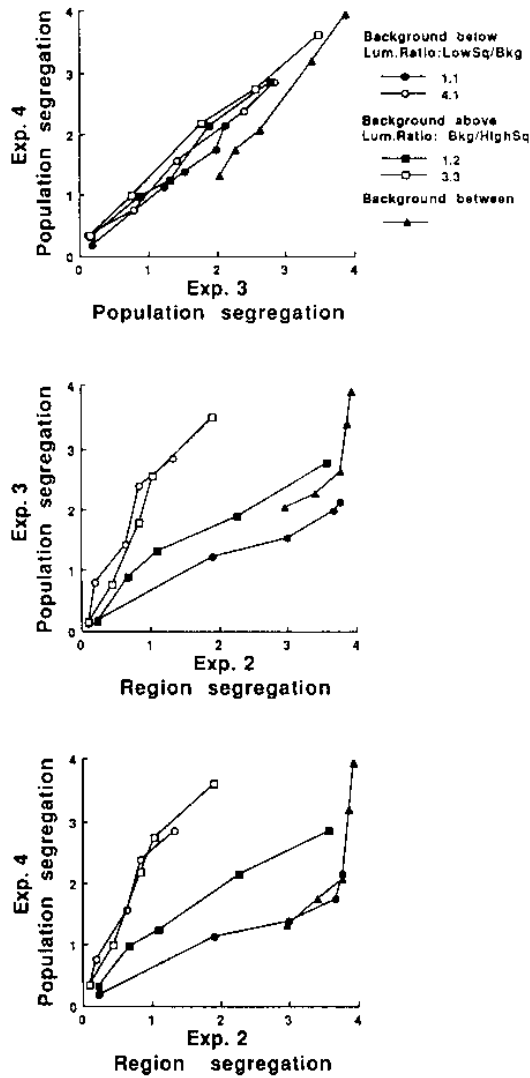


Figure 9. Mean segregation ratings in Experiments 2, 3, and 4, plotted against each other.

the lightness differences of the squares were not uniquely determined by their luminance ratios. Both lightness differences and perceived population segregation appear to have been affected in common by unspecified factors.

Lightness differences. The lightness matches in Experiments 3 and 4 are highly similar to those in Experiment 2 and to each other, as can be seen in Figure 10, in which the lightness differences in Experiments 2, 3, and 4 are plotted against each other. (Although only lightness differences are shown in Figure 10, it is also true that the lightness matches of the individual light and dark squares were highly similar.) The r^2 values for mono-

tonic nonlinear fits between Experiments 2 and 3, Experiments 2 and 4, and Experiments 3 and 4 ranged between .97 and .98 (see the Appendix).

The gain in lightness difference is controlled by the parameter k in Equation 1 and will vary with experimental conditions (Heinemann, 1989). In Experiments 3 and 4, as in Experiment 2, lightness differences increased much less steeply as a function of the luminance ratio of the lighter and darker squares when the luminance of the background was 3.3 times the luminance of the lighter square (open squares in Figures 6b, 6d, and 6f) than they did in other conditions. Thus, the value of k for the best-fitting logarithmic functions was much lower when the luminance of the background was 3.3 times that of the lighter square (unfilled square) than it was in the other conditions, in

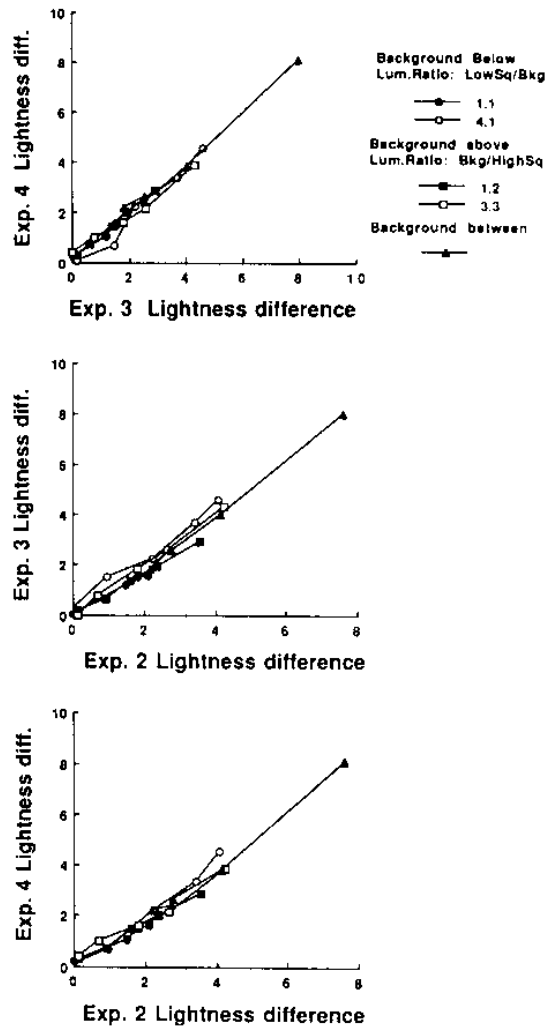


Figure 10. The mean of the differences in subjects' lightness matches in Experiments 2, 3, and 4, plotted against each other.

which the background luminance was either lower or higher than the luminance of both sets of squares (filled square, filled circle, unfilled circle). The values of k were 1.5-1.8 versus 10-15. The reason for this is unclear. For the condition in which the background luminance was between the two square luminances, the intercepts of the best-fitting logarithmic functions were quite far from zero (2.24-2.52 in the three experiments), suggesting that a logarithmic function was not a particularly good fit and that an even more compressive function would be necessary. (There was some tendency in this direction in the other conditions too; the intercepts were always positive, with values ranging from 0.05 to 0.90).

Figures 7b, 7d, and 7f show the lightness differences as a function of the ratio of the contrasts of the light and dark squares. As in Experiment 1, the data points fail to fall on a single line.

DISCUSSION

In summary, perceived lightnesses are much the same for given sets of squares, whether they are in texture regions (Experiment 2) or in intermixed populations (Experiments 3 and 4). Perceived population segregation (Experiments 3 and 4) is highly correlated with perceived lightness differences, but perceived region segregation (Experiments 1 and 2) is not.

In Experiments 1 and 2, segregation of the tripartite pattern into regions depends on detecting the difference in the arrangement of the squares. Since the pattern in those experiments contained regions composed of approximately equal numbers of light and dark squares of equal size, small bar, spot (even receptive fields), and edge (odd receptive fields) detectors can provide no information for segregating the pattern into regions. These detectors can indicate that there are two populations—light and dark squares. There is, however, no spatial differentiation as a result of their outputs. The equal spacing of the squares also precludes proximity grouping or cluster detection. The detectors that do show strikingly different outputs to the different arrangement of squares in the striped and checked regions are large bar detectors with large oriented receptive fields that are sensitive to the fundamental frequency of the texture regions (Sutter, Beck, & Graham, 1989). They respond to the periodicity of the pattern and signal the differences in the overall pattern of squares in the striped and checked regions. In the striped region, the changes of overall luminance occur in the horizontal direction, and in the checked region, they occur in a direction 45° from horizontal. When the relative contrasts of the light and dark squares are not sufficient to differentially stimulate large bar detectors sensitive to the fundamental spatial frequencies of the regions, the pattern then segregates not into three regions but into two subpopulations—light squares and dark squares. Sutter et al. (1989) have reported similar results for squares differing in size. In the present experiments and in Beck et al. (1987), perceived region segregation is heavily, but not completely,

dependent on the ratio of contrasts of the light and dark squares, except when the background luminance is between the luminances of the squares. (See Graham, Beck, & Sutter [1989, 1990] and Graham [in press] for more details of this dependence.)

Population segregation does not depend on the ratio of the contrasts of the light and dark squares in the way region segregation does. Population segregation could not be due to differences in the response of large bar detectors, because the light and dark squares are distributed randomly throughout the display; so the excitatory and inhibitory regions of the large bar detectors are stimulated by both light and dark squares. The mechanism by which region and population segregation occurs is also different. In region segregation, the outputs from the spatial frequency/orientation channels are used to establish boundaries between the regions. In the population displays, there are no boundaries between regions. The population segregation of a display into light and dark squares is an example of pure similarity grouping. A plausible mechanism is to suppose that elementary spot and bar detector systems detect bimodality with respect to a feature such as lightness and divide the original population into two subpopulations. Perceived segregation in Experiments 3 and 4, as opposed to perceived segregation in Experiments 1 and 2, is therefore more nearly a single-valued function of the lightness differences of the squares. Note too that unlike the region and population patterns investigated in the present paper, the segregation of line-like patterns in a background of distractors cannot be explained as a direct result of the differential stimulation of spot and bar detectors. Line segregation appears to involve element grouping mechanisms that operate on the outputs of small bar, spot, and edge detectors (Beck, Rosenfeld, & Ivry, 1989).

How the perceived lightnesses of the squares depend on the luminances of the squares and the background is not completely clear. The large bar detectors primarily responsible for perceived region segregation do not have the right properties to signal the lightness of the homogeneously illuminated squares, because they average over several squares. Information for the perception of lightness could be given by the small symmetric receptive fields, which would respond to the individual squares, and by the odd symmetric receptive fields, which are thought to be involved in localizing edges. Lightness has been taken to be a function of the ratio of the luminance of a stimulus and the adaptation level (Helson, 1964), or of the ratio of the luminance of a stimulus to the background (Wallach, 1948). It has also been argued that the visual system responds only to contrast at its borders, and that lightness is determined by the luminance ratio of edges (Grossberg, 1987; Grossberg & Todorović, 1988; Land & McCann, 1971; Shapley & Enroth-Cugell, 1985). The responses of these detectors to the light and dark squares would not be greatly affected by the differences in the arrangement of the squares in Experiments 2, 3, and 4. It is therefore not surprising that the lightness difference judgments are similar in Experiments 2, 3, and 4.

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NOTES

1. *Contrast* was defined here as the difference between the luminance of a square and the average of the luminances over the entire pattern, divided by the average luminance. This is an extension of the quantity that Shapley and Enroth-Cugell (1985) call *Rayleigh contrast* for periodic patterns.

2. *Contrast* was defined here as the difference between the luminance of a square and the luminance of the background, divided by the luminance of the background. The background luminance is not the same as the average luminance, but often, as in the present instance, it is close enough so that it can be used in its place.

APPENDIX

In a number of places in this paper, r^2 values (the proportion of variance in y accounted for by x) are reported for the fit of a nonlinear monotonic function to two observed variables x and y (where, e.g., x might be the average matched lightness difference for each of the stimuli in an experiment and y the average perceived segregation rating). Ideally, for our purposes, this value would have been computed from the best-fitting function f of all possible monotonic functions. For practical purposes, however, we had to limit ourselves to families of monotonic functions describable in simple equations. For the fits reported here, we assumed that f was a member of either of two particular four-parameter families of functions. These families were picked merely because they contained the right variety of shapes to fit the task at hand. Both were used to make sure that the particular choice of family did not distort the results. The first family is a slight generalization of the Weibull distribution or Quick psychometric function (e.g., Graham, in press) and of the asymptotic regression function (see, e.g., Snedecor & Cochran, 1980):

$$y' = f(x) = a(b + 1 - 2^{-(c \cdot x)^d})$$

The second family is a slight generalization of what has been called the Naka-Rushton or hyperbolic tangent function (see, e.g., Hood & Finkelstein, 1986):

$$y' = f(x) = a \left(b + \frac{x^n}{x^n + \sigma^n} \right)$$

The Nelder-Mead algorithm (which is nicely described in Press, Flannery, Teukolsky, & Vetterling, 1986), as instantiated in MatLab for the Macintosh II computer, was used to find the four parameters for producing the smallest mean square error (over all the stimuli in the comparison at issue) between the predicted y' and the observed y . The reported r^2 is the Pearson product-moment correlation between the predicted y' and the observed y .

In nonlinear curve fits, the r^2 obtained in predictions of x from y is not necessarily the same as that in predictions of y from x , but they are typically close.