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Grouping in Sparse Random-Dot Patterns: Linear and Non-Linear Mechanisms

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ABSTRACT

This study reports on experiments conducted with human observers to investigate the properties of linear and non-linear, perceptual grouping mechanisms by using reverse-polarity sparse random-dot patterns. The stimuli were generated by spatially superimposing a sparse set of randomly distributed square elements onto a copy of the original set that was expanded or rotated about the center of the screen. In the control experiment both the original and transformed sets contained elements of identical luminance contrast with the background. The main experiments involved a reverse-contrast random-dot pattern, in which the transformed set consisted of elements of equal contrast magnitude but opposite polarity to that of the original set. At least two competing global percepts are possible: "Forward grouping" in which perceived grouping agrees with the physical transformation; or "reverse grouping" in a direction orthogonal to that of the "Forward grouping". The two-alternative forced-choice (2AFC) task was to report the direction of the global grouping. For the control experiment, the observers reported forward grouping both at the fovea and eccentricities of up to 4 degrees; as expected, no reverse grouping was observed. With the reverse-polarity stimulus, reverse grouping was observed at high eccentricities and low contrasts, but forward grouping dominated under foveal viewing. In another experiment, the influence of chromatic mechanisms was studied by using opposite-contrast red elements on a yellow background. In this experiment reverse grouping was not observed, which indicates that color mechanisms veto reverse grouping. Reverse grouping can be hypothesized to be the result of processing by linear oriented spatial mechanisms, in analogy with reverse-phi motion. Forward grouping, on the other hand, can be explained by non-linear preprocessing (such as squaring or full-wave rectification).

Keywords: Psychophysics, Glass patterns, perceptual grouping, Fourier and non-Fourier mechanisms

1. INTRODUCTION

A target shown on multiple frames with a slight displacement to the right in each frame is perceived as motion in the rightward direction (Fig 1a). The dominant Fourier component, shown schematically superimposed on the stimulus, is a sinusoidal grating moving to the right at the same velocity as the square target. Thus in this case the direction of the dominant Fourier component coincides with the percept. However, if the polarity of the target displaced to the right is reversed in subsequent frames, as shown in Fig. 1b, the percept is that of leftward motion. This percept, known as reverse-phi motion, is observed for peripheral viewing (Anstis[1]) and fast presentation times. When viewed foveally at slow presentation times, the percept is that of (veridical) rightward motion. A Fourier analysis of this stimulus reveals that the direction of the dominant Fourier component is towards the left, which is in accordance with our percept at peripheral viewing. The percept at foveal viewing, however, cannot be explained by Fourier

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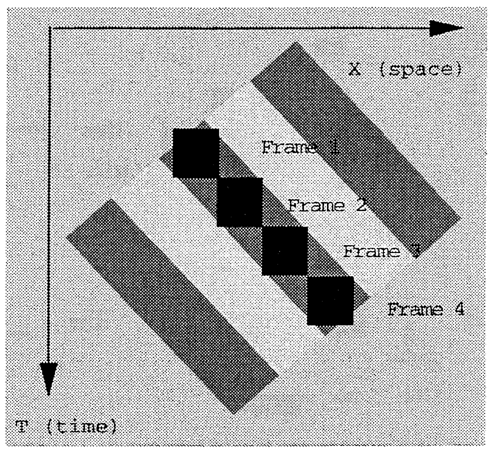
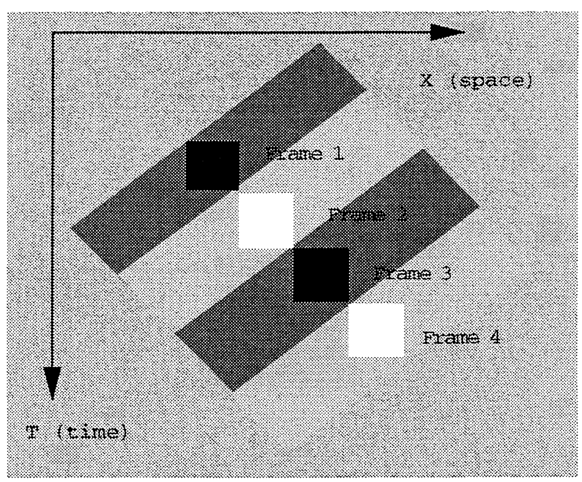
like mechanisms and hence has to be mediated by non-Fourier like mechanisms. Thus motion perception can be thought of as mediated by two types of mechanisms, namely the Fourier or linear mechanisms and the non-Fourier or non-linear mechanisms. Just as with motion, humans can perceive grouping in what we call Fourier and non-Fourier random-dot stimuli, depending on whether they do or do not have energy in specific regions of the frequency domain, respectively. This is a very important finding, because it underlines the importance of linear mechanisms in grouping. It points to a new direction, because the implicit assumption in this area of research has been that grouping is the result of mostly nonlinear process. The purpose of the present study was to investigate the roles of linear and non-linear mechanisms in perceptual grouping, and to assess their relative sensitivities*



a) Dark square moving to the right



b) Alternate dark and bright squares moving to the right

Figure 1. a) Motion of square elements to the right. The dominant Fourier component of this stimulus (shown schematically as dark and bright bands) is superimposed on the stimulus. b) Alternate dark and bright squares (reverse polarity stimuli) and the dominant Fourier component

*We use the terms Fourier, linear and first-order interchangeably in this paper and similarly the terms non-Fourier, non-linear and second-order.

2. METHODS

2.1. Grouping - Stimuli

The stimulus was generated on a Silicon Graphics IRIS raster display system. Accurate timing is insured within 16.667 ms, because the IRIS provides access to the vertical blanking signal at a video rate of 60 Hz. Images are viewed 100 cm from the observer. At that distance, the width of the square elements (targets) subtended 7' of visual angle. The entire window size subtended a width of 20^0 and a height of 18^0 of visual angle.

The stimuli were generated by spatially superimposing a sparse set of randomly distributed square elements (length 7' of visual angle) onto a copy of the original set that was expanded or rotated about the center of the screen. In the control experiment both the original and transformed sets contained elements of identical contrast against a yellow background. The control experiment stimuli shown in Figure 2 is a typical example of the random-dot pattern stimuli which is also known as the Glass pattern stimuli.[2] As shown in Figure 2 the percept is a circular pattern.

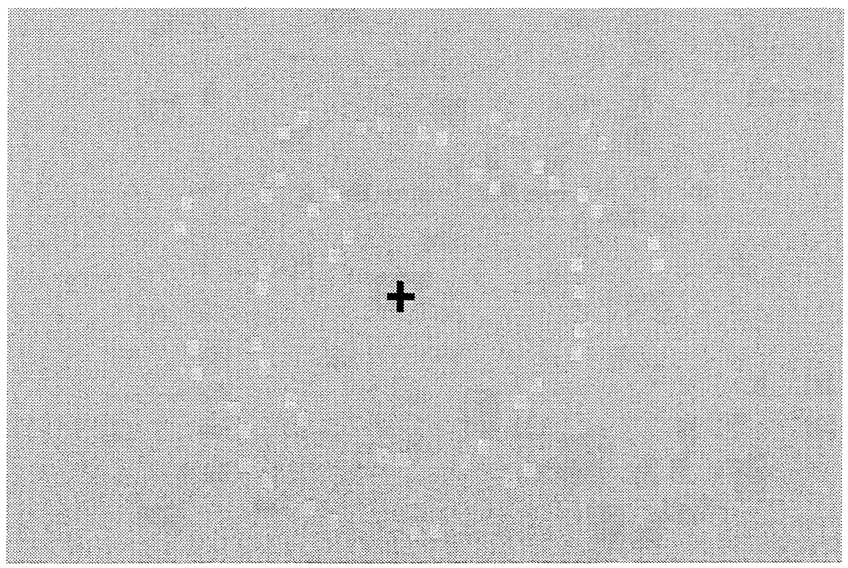


Figure 2. Sparse random-dot stimulus where the global percept is of a circular pattern.

The main experiments in this study involved a reverse-contrast random-dot pattern, in which the transformed set consisted of elements of equal contrast magnitude but opposite polarity to that of the original set (Figure 3). At least two competing global percepts are possible: "Forward grouping" in which perceived grouping agrees with the physical transformation; or "reverse grouping" in a direction orthogonal to that of the "Forward grouping". The stimulus in Figure 3 can give rise to one of two percepts as shown in Figure 4 based on forward or reverse grouping †.

2.2. Experimental Setup

A two-alternative forced choice (2AFC) procedure was used. The observer was asked to report the global direction of grouping (tangential or radial) pattern. The direction of grouping was randomized from trial to trial. The percentage favoring "forward" grouping was measured as a function of contrast, eccentricity and size of elements. A fixation point was used at the center of the width of the window, and the experiment was repeated at various distances (eccentricities) of the elements from the fixation point. Stimulus duration was limited to 64 ms to avoid initiation of eye movements and scrutiny of stimuli. There was no mask used in the experiments.

† The forward and reverse percepts are obtained at short stimulus durations of about 100 ms and may not be obvious while looking at them in Figure 3

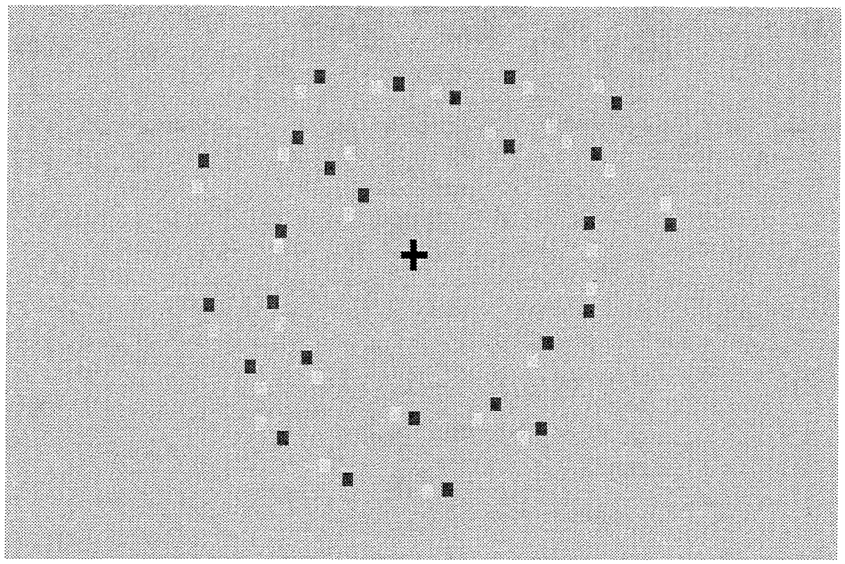


Figure 3. Reverse polarity random-dot patterns. The elements have equal magnitude luminance contrast but opposite polarity with respect to the background.

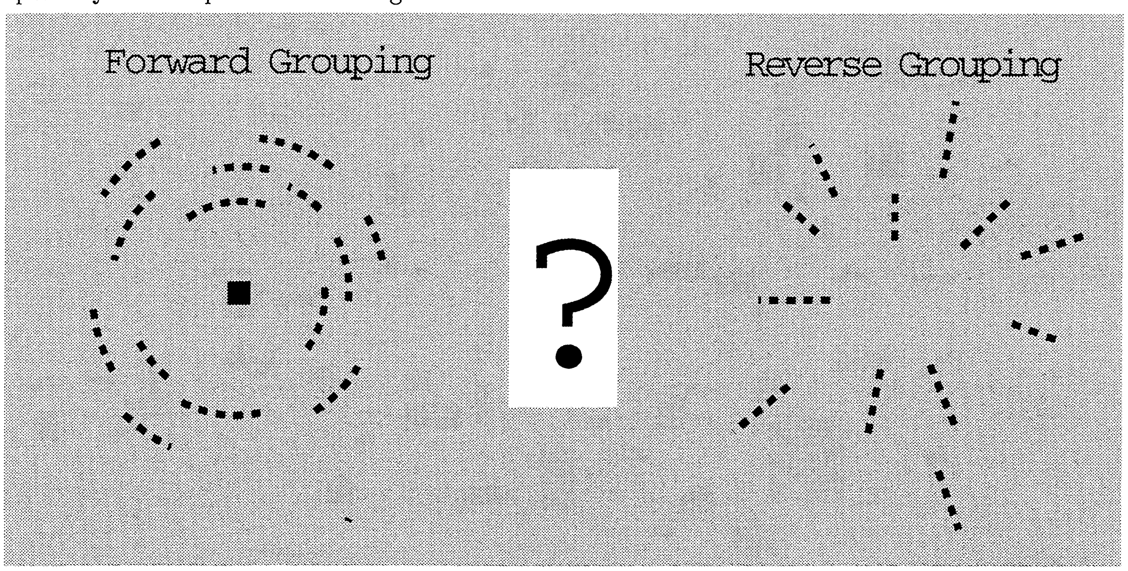


Figure 4. The two percepts for Figure 3. "Forward grouping" would lead to a circular pattern and a "reverse grouping" would give rise to a tangential pattern.

2.3. Experiments

One of the authors (RSK) and two other naive but well trained observers (JW, EU) participated in all experiments. Vision was binocular with natural pupils and corrected to normal. Two sets of experiments were conducted. In the first set of experiments the background was chosen to be medium grey with a luminance of 20 cd/m^2 and the elements had equal contrast magnitude with respect to the background but opposite contrasts. With the same configuration three subsets of experiments were conducted. In the first subset, the eccentricity was fixed at 2.01^0 and the size of the elements (length of a square) fixed at 4' of visual angle. The performance expressed as % favoring forward grouping was measured as a function of contrast. In the second subset, the performance was measured as a function of eccentricity (size and contrast was fixed) and in the third the performance was measured as a function of element size (eccentricity and contrast was fixed). Prior to conducting the first set a control experiment was run with stimulus shown in Figure 2 with various levels of contrasts (magnitude and polarity equal for both the original and transformed sets).

In the second set of experiments, the influence of chromatic mechanisms was studied by using elements with chromatic contrasts with the background. The background was chosen to be yellow and its luminance was varied (independent variable) in all the experiments which involved color. Three subsets of experiments were conducted. In the first subset both the original and transformed elements were identical (both red or green) with a luminance value of 20 cd/m^2 and the luminance of the yellow background was varied from 14 to 26 cd/m^2. The aim of this experiment was to study the influence of chromatic mechanisms on grouping especially at the point of equiluminance. It would be expected to have minimum performance at the point of equiluminance since at this point there is no luminance difference between the elements and the background and the grouping (if perceived) should be only due to chromatic influences. In the second subset of experiments the elements have the same color as the background but difference luminance values and as before the luminance of the yellow background was varied. In the third subset of experiments the original and transformed elements have the same color (red or green) but different luminant values and the luminance of the yellow background is varied.

3. RESULTS

The results of the first experiment (reverse contrast luminance stimuli) are plotted in Fig. 5. Along the horizontal axis are plotted percentage contrast values of the square elements with respect to the background. The ordinate is the % favoring "forward" grouping. At low values of contrasts the % favoring "forward" grouping is less than 50%. This indicates that observers begin to perceive the opposite, or reverse, grouping. However, at very low contrasts the curve is near chance level (50%) since at such low contrasts the elements are barely visible and hence grouping is ambiguous. At very high contrasts performance reaches 100%, indicating that the forward grouping dominates the percept. There is a medium contrast value at the transition between "reverse" grouping and "forward" grouping, which we denote as C*, which produces ambiguous grouping direction (50% favoring either grouping). Thus the graph is divided into two domains: a) contrast $<$ C*, which favors "reverse" groupings, which can be explained by Fourier or linear mechanisms and b) contrasts $>$ C*, which favors "forward" grouping, and can be explained by non-Fourier or non-linear mechanisms. One possibility is that the output of the front-end linear filters is first full-wave rectified, before feeding the mechanisms that are responsible for spatial grouping. Full-wave rectification can be achieved by an energy mechanism which essentially takes the absolute value of the luminance-polarity of the elements, and further grouping can be achieved by a similarity metric. Thus at C*, the outputs of the two mechanisms are equal, resulting in an ambiguous grouping. A high value of C* signifies a larger contrast range over which Fourier units dominate. Note that in the data plotted in Fig 5 the ordinate value never goes to 0%, indicating that the Fourier units never completely dominate over non-Fourier ones.

For the control experiment,with the stimulus shown in Figure 2 the observers reported forward grouping both at the fovea and eccentricities of up to 4 degrees; as expected, no reverse grouping was observed as shown in Figure 6. The results of the second experiment which studies the effects of eccentricity on linear mechanisms are plotted in Fig 7. Results are shown at three values of eccentricities for one observer. There were only small inter-observer differences. Fig 7 refers to the plot when the experiments were done with reverse polarity stimuli at the fovea (zero eccentricity) and eccentricities of 2^0 and 4^0. As shown in the plot the range of linear or Fourier mechanisms increases with increasing eccentricities. The third experiment (with reverse polarity luminance only random-dot patterns) in this study reveals the effect of element size on reverse grouping. The variable size is defined as the length in visual angle of the square element. The geometry was identical to that shown in Fig 3. As indicated in Fig. 8 the range for linear mechanisms increases as the element size decreases.

The second set of experiments were conducted to investigate the influence of chromatic mechanisms on forward and reverse grouping. The result of the first subset which involves identical elements (green) on a yellow background is shown in Figure 9. The plot indicates that the forward grouping is always perceived at all background luminances including the point of equiluminance (with the elements).

The results of the control experiment in color is shown in Figure 10. Here the elements have the the same color as the background but different luminances. Chance level (50%) performances are observed at two positions corresponding to the background luminances values which equal to the element values. For all the background values

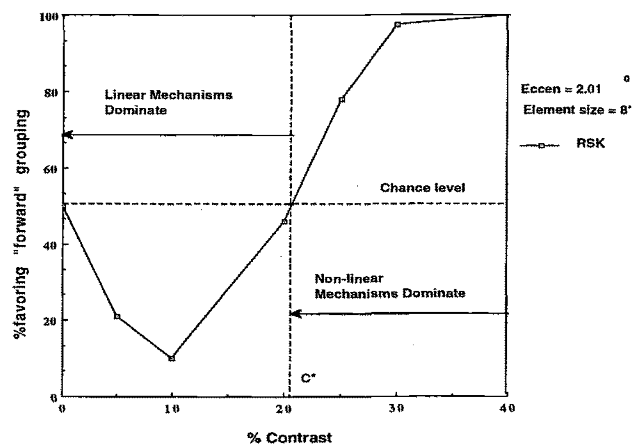


Figure 5. Reverse grouping occurs at low contrasts

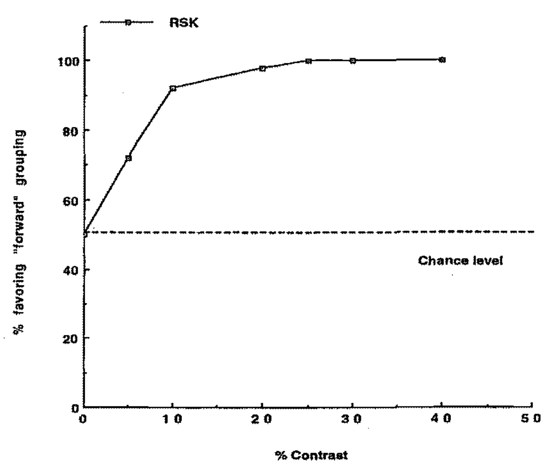


Figure 6. Forward grouping with same polarity random-dot patterns.

which are in between the element luminances, reverse grouping is observed. In the other portions forward grouping is perceived.

The final experiment involved luminance contrast between the elements themselves and that of the background and chromatic contrast between the elements and the background. The result of this experiment is shown in Figure 11. In this experiment reverse grouping was not observed, which indicates that color mechanisms veto reverse grouping.

4. DISCUSSION

The results show that reverse grouping is favored by low contrast, high eccentricities and small element sizes. These results extend Sperling's[3] notion of two systems or mechanisms of visual processing to the perceptual grouping domain. The non-linear or non-Fourier mechanisms which are responsible for forward or veridical grouping may be

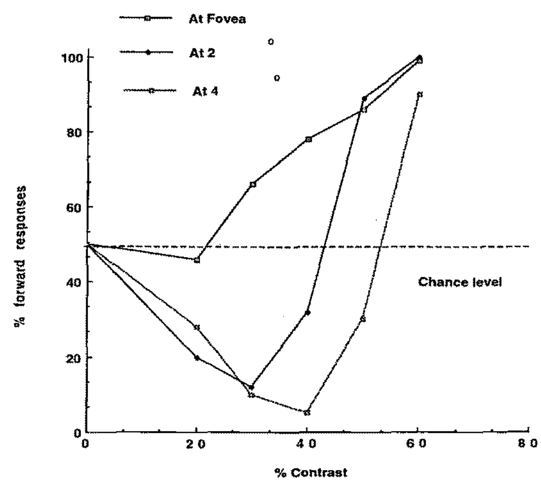


Figure 7. Effects of eccentricity. As eccentricity is increased the linear or Fourier mechanisms dominate.

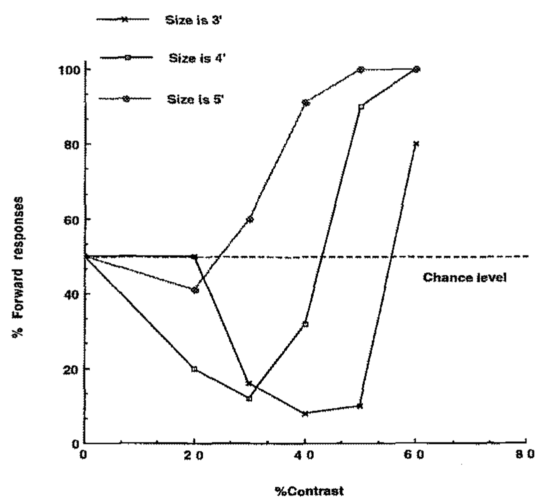


Figure 8. Effects of element size. As the element size is reduced, the curve is shifted to the right indicating dominance of the Fourier mechanisms at small element sizes.

built by complex cells. They can either be a full-wave rectifier system or an energy system which are blind to polarity differences, but have a preferred orientation. This type of receptive field is shown in Figure 12. The linear or Fourier mechanisms may be built by receptive fields of simple cells, as shown in Figure 12 and are the characteristic Hubel & Weisel[4] type orientation units.

We have used sparse random-dot stimuli to reduce the effects of collinearity (Field et al.[5]), which favors the non-Fourier units (Full-wave rectifier). Orthogonal or reverse grouping has been observed for dense Glass patterns (Anstis[1]; Kovacs & Julesz[6]; Papathomas et al.[7]), but it has a simple explanation on the basis of stochastic spatial processes in the stimulus space (Prazdny[8]).

Our experiments with color indicates that color plays a dominating role in perceptual grouping. Presence of color

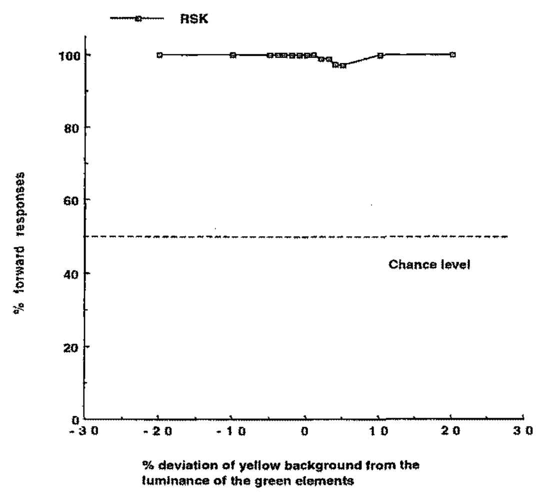


Figure 9. Influence of chromatic mechanisms. Forward grouping is always perceived including the point of equiluminance.

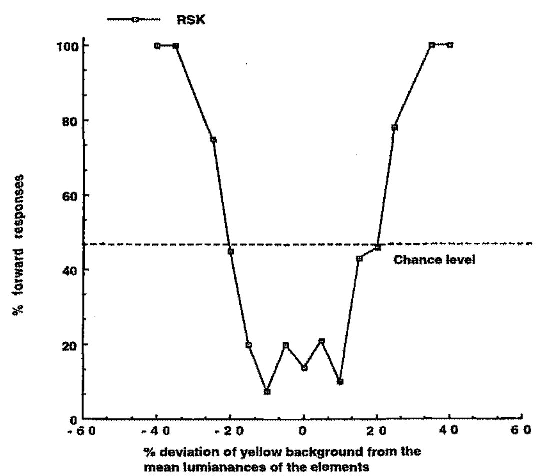


Figure 10. Control experiment in color. Reverse grouping is perceived for background luminances which are in between the element luminances.

overshadows the linear or Fourier mechanisms and hence vetoes reverse grouping.

5. CONCLUSIONS

Reverse grouping can be hypothesized to be the result of processing by Fourier (linear or quasi-linear) oriented spatial mechanisms, in analogy with reverse-phi motion (if speed in x-t space is viewed as analogous to orientation in x-y space). Forward grouping, on the other hand, can be explained by non-linear preprocessing (such as squaring or full-wave rectification). A natural extension of this study would be to study forward and reverse grouping with bi-chromatic stimuli, i.e., substituting dark with equiluminant red, and bright with equiluminant green targets on an equiluminant yellow background.

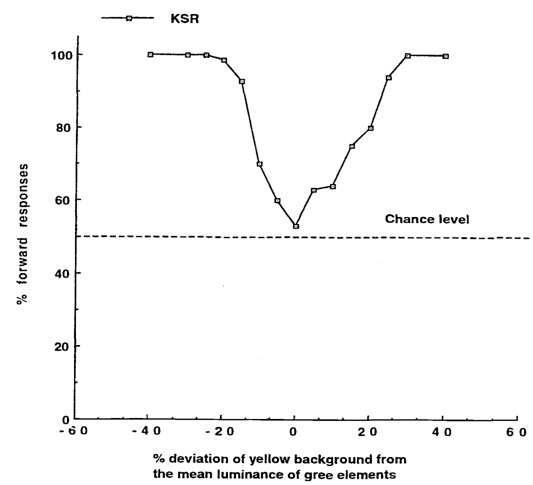


Figure 11. Reverse grouping is vetoed in the presence of color

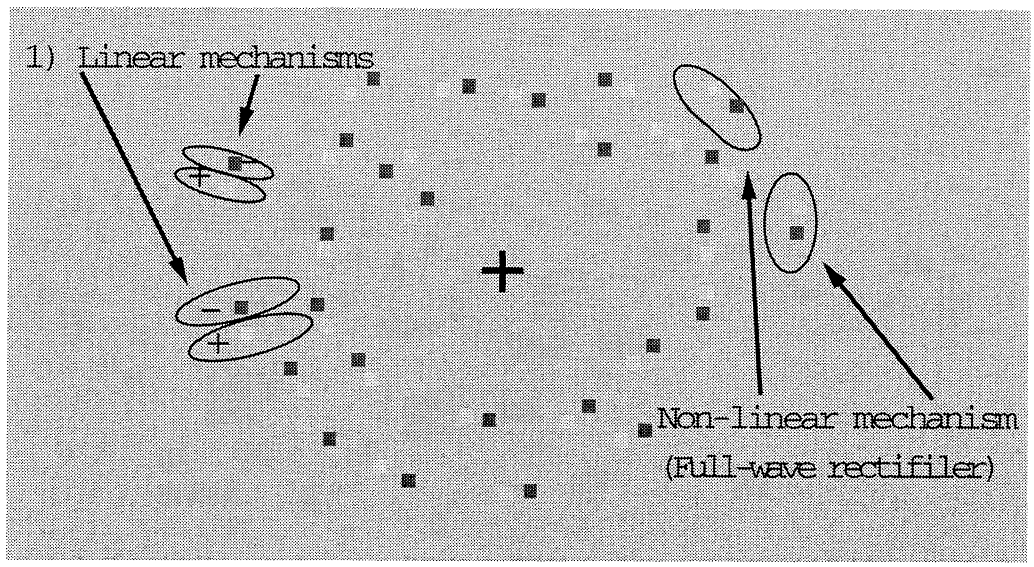


Figure 12. Linear and non-Linear mechanisms involved in textural grouping.

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