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ABSTRACT

We report on several experiments that we designed to study the relative strength of visual attributes in the perception of texture. Our stimuli are composed of microelements that are arranged regularly in two-dimensional space. Each microelement can be characterized by the conjunction of several attributes (shape, size, color, etc.). Although the spatial regularity results in a "homogeneous" texture, we can manipulate the arrangement of selected attributes so as to break this homogeneity by forming textural patterns, whose discriminability can be tested experimentally.

The stimuli allow flexibility in choosing the ways in which different attributes can be matched spatially to generate patterns. We have used these stimuli to study the roles of color, orientation, luminance and polarity in forming textures. Preliminary results indicate an inherent similarity between the mechanisms subserving texture perception and those mediating the perception of motion; the latter were studied with a similar type of stimuli. Finally, we report on a method for isolating the role of specific texture mechanisms by comparing the results of carefully selected experiments.

1. INTRODUCTION

Motion, depth and texture perception are three important areas of study in low-level vision. Among them, the first two share a lot of similarities: for random-dot cinematograms (RDC) there exists a critical target displacement, d_{max}, depending on stimulus properties, which must not be exceeded if coherent motion perception is to be elicited.[1-5] The analogue of d_{max} in random-dot stereograms (RDS) is the maximum allowable binocular disparity which still results in stereoscopic fusion.[6-10] Another point of similarity is the putative existence of two types of mechanisms for the perception of both motion and stereo: global or short-range mechanisms and local or long-range mechanisms[1,2,7] (although such a clear dichotomy has been contested recently by Cavanagh and Mather[11] in the case of movement perception). A third piece of evidence for the similarity of the two modules of stereo and motion is the kinetic depth effect (KDE),[12] which owes its name to the vivid perception of three-dimensional (3-D) shape one experiences from an animated sequence of two or more two-dimensional (2-D) images of an object obtained by rotating the object. Of course, such similarities between movement and stereopsis are expected, since the first deals with two (or more) images seen in two (or more) different instants in time, whereas the second also involves two images, but as seen from two different points of view.

The relationship of texture perception mechanisms to those of either motion or depth perception is not as straightforward. The inherent difference is that *texture* deals with a *single* 2-D image, whereas both *movement and stereo* require at least *two* 2-D images. However, it *is* possible to compare texture and movement perception if we confine the latter to uni-dimensional (1-D) motion.[13,14,15] In this case we can obtain a 2-D representation of the motion stimuli if we map the temporal axis onto the spatial y-axis for uni-dimensional motion along the x dimension; this scheme was used, among others, by Adelson and Bergen,[13] who called the 2-D space that resulted from such a mapping the "x-t space." Images in the x-t space, although meant as a convenient vehicle to visualize 1-D motion, *can be* viewed as *textures* (see, for example, Figures 16 and 17 of Adelson and Bergen,[13] Figures 1 and 4 of Chubb and Sperling,[14] and Figures 2b and 3 of Papathomas and Gorea[15]). It is this analogy between texture and the special case of 1-D motion that we wish to report on in this paper.

2. STIMULI

Before describing our texture stimuli, we briefly consider some commonly used techniques for studying texture segregation and outline our x-t plane motion stimuli.

2.1 Some methods for forming and studying texture

Most researchers who have studied texture perception have concentrated on textures that are formed by micropatterns, called *textels,* that are repeated in space at random locations and orientations.[16,17] Examples of textels are: straight line segments, arcs, circles, letters such as "T", "L", "X", etc. Most often, the background is displayed at a uniform luminance, whereas the textels' luminance is fixed at a different value, resulting in bi-level images; multi-level (gray-level) images are far less frequent. One common method for studying texture segregation is to form a target texture patch using one textel, say "L", and to imbed this patch in a surround texture formed by another textel, such as "T". The ease of discriminability of the target patch by the observer is then used to study the role of the textel properties in forming texture gradients. One alternative method is to display a single target textel among many distractors and study detectability.[18,19]

The above techniques concentrate on differences in the figural, or form, features (attributes) of the surround and target textels, while all other features (luminance, color, stereo disparity, etc.) are held constant. The conjunction of two attributes has also been studied, among others, by Treisman and Gelade,[19] Nakayama and Silverman,[20,21] Walters, et al.[22] and Sagi,[23] using variants of the second method mentioned in the previous paragraph. The texture stimuli, presented in subsection 2.3, are very relevant to these studies, because they allow the formation of textures by textels that are defined by the conjunction of multiple attributes.[24] Since our stimuli have originated from a class of x-t motion stimuli,[15,25] the next subsection is devoted to outline briefly this class.

2.2 A class of motion stimuli

Consider the x-t diagram of Figure 1. The horizontal axis is the spatial variable x, discretized by the index j, along which motion is perceived. The vertical axis is time t, discretized by the index i. The zeroth row is shown at $t=t_o$ and it is replaced in sequence at $t=t_o+i\Delta t$ by the ith row (i=1, 2, . . .). The elements occupy periodic positions in the spatiotemporal plane and can be of any arbitrary shape. If all the elements are identical (ignore, for the time being, the labels of the elements), the direction of the ensuing apparent motion (AM) will be ambiguous, since the inter-frame displacement, Δx, between elements, is half the intra-frame inter-element distance x_o=p+q.

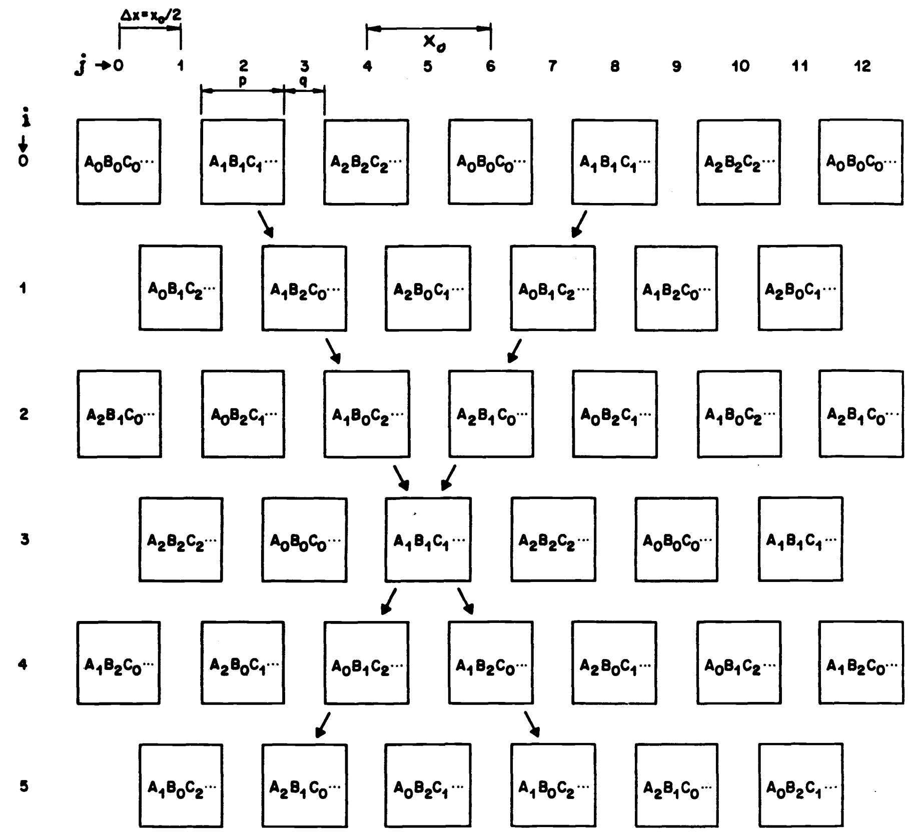

Figure 1: Schematic representation of the multi-attribute stimuli that can be used either for motion or texture perception studies.

If, however, we define each element by the conjunction of attributes A, B, C, . . . (such as color, orientation, size, spatial frequency, etc.), then this ambiguity may be resolved. For example, in Figure 1, notice that the subscripts of A and B, denoting the different values of attributes A and B, are arranged in the spatio-temporal domain in such as way as to produce motion to the right and to the left, respectively; attribute C's distribution, on the other hand, does not contribute to unambiguous, coherent motion, since its values are not matched to produce either leftward or rightward motion. If attributes A and B are tokens for motion, they will try to elicit motion perception in competing directions *simultaneously*; which of the two directions dominates depends primarily on the strengths of A and B in inducing motion, on the sets of values ($\{A_o, A_1, A_2\}$ and $\{B_o, B_1, B_2\}$) used, and secondarily, on other parameters such as Δx, Δt, viewing distance, etc. Thus, such stimuli can be used to compare directly the relative strength of two attributes in eliciting motion.[15,25]

2.3 Multi-attribute stimuli for texture perception

In addition to being useful for studying uni-dimensional movement perception, viewed one row at a time (as explained in the previous subsection), Figure 1 can also be employed to form texture stimuli in which the role of selected attributes can be studied systematically. The only difference is that the vertical axis of Figure 1 now corresponds to the spatial variable y, discretized by the index i; consequently, for texture studies, Figure 1 is seen all at once as a 2-D pattern. In fact, Adelson and Bergen[13] originally used the x-t plane as a convenient visualization tool for explaining convolution by spatio-temporal filters in the x-t plane, much the same way as one would do in the more familiar x-y image plane, which is also easier to understand visually. Unless otherwise specified, for the rest of this paper we will use Figure 1 as a 2-D image for texture formation purposes.

In Figure 1, attribute A is arranged in 2-D space to give rise to a global textural grouping that forms diagonal stripes with *negative* slope (from the upper left toward the lower right); notice that the values of A are fixed along these diagonals, whereas they vary cyclically along the *positive* diagonals. Attribute B forms stripes along the positive diagonals; its values are distributed in a dual fashion to those of A's. Notice that, although the positions of the textels in Figure 1 produce a uniform, homogeneous arrangement that doesn't favor either the positive or the negative diagonals, this homogeneity is broken by the appropriate distribution of the attributes' values. Attribute C's distribution does not form a coherent textural pattern, because its values vary cyclically along both the positive and the negative diagonals.

Of course, Figure 1 is but one example of how multiple attributes can be arranged in 2-D space to form textural grouping. An arbitrary number of attributes can be employed and each attribute can be distributed independently of the others. The number of values for each attribute, shown by the subscripts of A, B and C in Figure 1 is also arbitrary. This allows flexibility in designing experiments with this set of stimuli.

We emphasize that the texture elements (textels) of Figure 1, shown schematically as squares, are merely used to denote the canonical position. The textels themselves are formed by conjunctions of the visual attributes A, B, C, ... In a simple case when we wish to examine the role of only two attributes, say luminance and orientation, the elements can be as simple as oriented bars of different luminances (see Figure 2). When more attributes are involved, say luminance, orientation, color, spatial frequency, size and depth disparity, then Gabor patches can be used to form conjunctions of all these features (see, for example, Figure 3 in reference 15).

Figures 2a and 2b offer two illustrations in the special case where only two attributes (luminance and orientation) are involved. In Figure 2a, luminance is arranged to form negative diagonals (like A of Figure 1) and orientation tends to form positive diagonals (like B of Figure 1), a situation that we call *competitive* matching. In Figure 2b, luminance is matched as in Figure 2a, but now orientation is arranged cyclically along both diagonals, thus producing no coherent global stripes (like C of Figure 1). This is what we term "matching of luminance *across* orientation." If luminance were matched as in Figures 2a and 2b but the orientation were fixed across the entire image, then this would result in the arrangement that we term "matching of luminance *within* orientation." Naturally, we can also produce images in which orientation is matched *across* or *within* luminance. Finally, another interesting arrangement is one in which luminance and orientation are matched so that *both* produce global textural groupings in which the stripes are along the *same* diagonal, which we call *concurrent* matching.

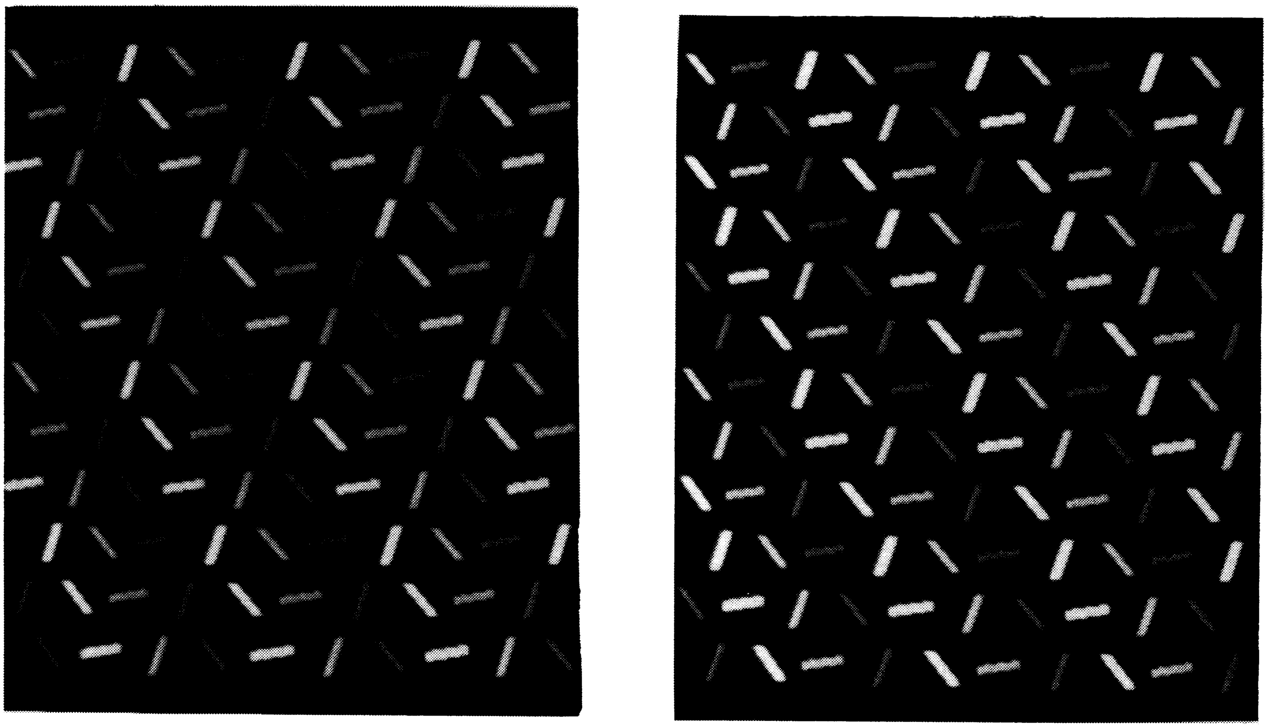

Figure 2: Specific examples of stimuli whose general form is shown in Figure 1. a) Competitive matching of luminance and orientation. b) Matching of luminance across orientation.

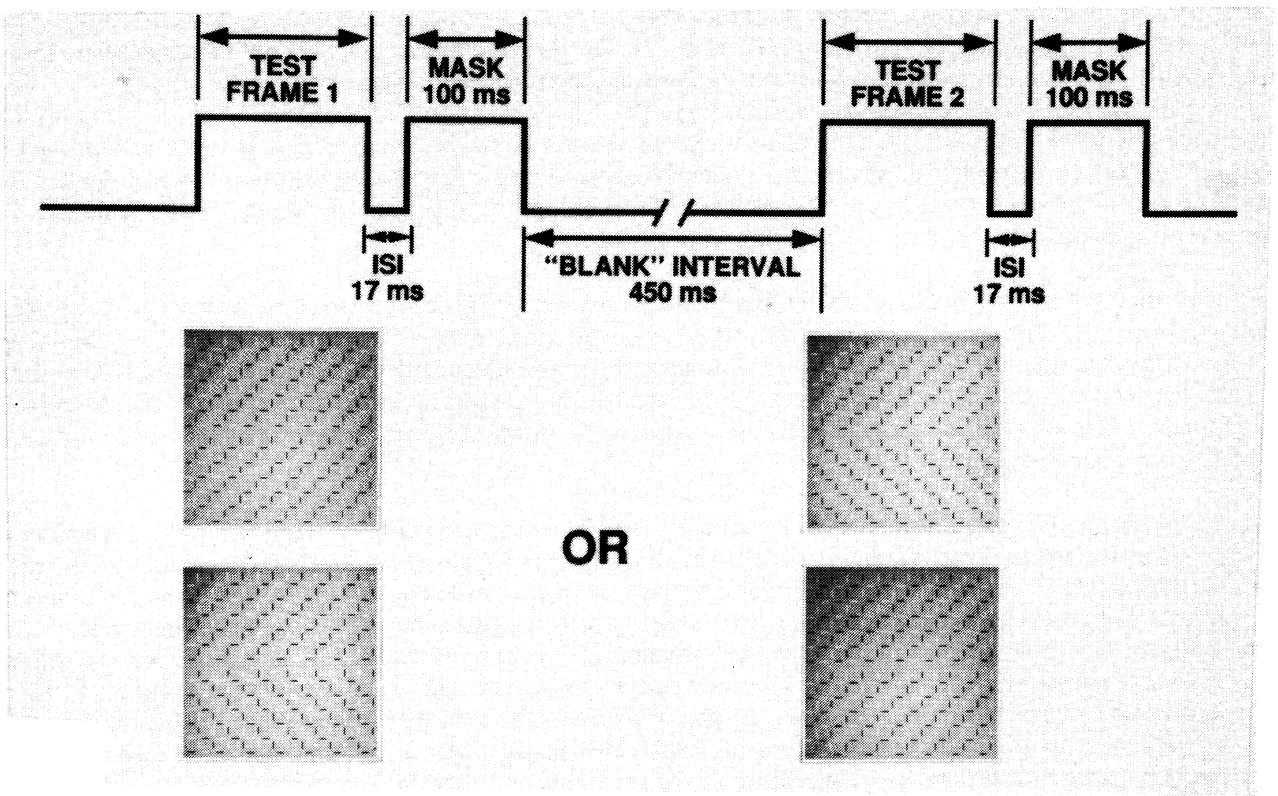

Figure 3: Top - Schematic diagram of the timing sequence used in the experiments. Bottom - Examples of stimuli.

3. EXPERIMENTS - RESULTS

Variants of stimuli that are based on the concept illustrated by Figure 1 have been employed in several groups of experiments on texture perception. We will outline the method used in all of these experiments in subsection 3.1 and we will present results of two such groups of experiments in subsections 3.2 and 3.3.

3.1 Methods and stimuli

In both groups of experiments reported in this paper, the elements are defined by two attributes A and B, with all other attributes held fixed. In the first group, A = orientation and B = luminance; in the second one, A = orientation and B = luminance-polarity. Various 2-D arrangements that were meant to produce textural grouping were tried within each group of experiments; such arrangements included matching of A *within* B, A *across* B, as well as B *across* A.

3.1.1 Experimental procedure

For each possible arrangement, all the images in our experiments were composed of two parts, the upper half and the lower half. Within each half the global diagonal stripes, formed by textural grouping (see subsection 2.3), were of either positive or negative slope. However, there were two possibilities for combining the patterns of the upper and the lower halves in each image: either a) both halves contained diagonal stripes of identical slope (either both positive or both negative) resulting in an "overall diagonal" pattern, or b) the two halves contained diagonal stripes of opposite slopes, resulting in (leftward or rightward pointing) "arrow-tail" or "chevron" patterns. These two possibilities are illustrated in Figure 3, with positive-slope overall diagonal and leftward pointing arrow-tails.

Observers were shown a sequence of images, as shown in the schematic diagram at the top of Figure 3. Test frame 1 contained the "overall diagonal" or the "arrow-tail" pattern; test frame 2 contained the arrow-tail or the overall diagonal arrangement, depending on whether test frame 1 displayed the overall diagonal or the arrow-tail pattern, respectively. [Of course, we also had a negative-slope overall diagonal configuration, as well as rightward pointing arrow-tails, for a total of four possible combinations of test frame patterns, but these are not shown in Figure 3]. The task of the observer was to indicate which test frame contained the arrow-tails. Each test frame was followed by a 100ms mask after a 17ms inter-stimulus interval (ISI); the two test frame/mask sequences were separated by a 450ms blank interval.

The performance of the observers was obtained as the average of percent of correct responses, as a function of stimulus duration, which was limited to 233ms, to avoid initiation of eye movements. For each value of stimulus duration, 50 trials were produced in a session. At least one session was tried for each condition reported (the average number of sessions was 2.84, corresponding to an average of 142 trials for each condition). In each trial, the sequence of patterns for test frames 1 and 2 was randomized. The type of stimulus (A within B, A across B, B across A, etc.) and the stimulus duration were both randomized from session to session.

3.1.2 Details on the generation and display of the stimuli

The textels were long bars, 1.2 arcmin by 10.5 arcmin when viewed from a distance of 200 cm, at two orthogonal orientations (0 and 90 degrees). They were generated on an ADAGE RDS3000 raster display system, driven by a VAX11/750 minicomputer. There were 12 rows of such bars above and 12 rows below the fixation point which was displayed at the center of the image (not shown in Figure 3). The horizontal distance between adjacent elements in a given row was 21 arcmin, whereas the distance between successive rows was 10.5 arcmin. The entire image subtended 4.55 degrees of visual angle both vertically and horizontally at a viewing distance of 200 cm.

In the next two subsections we report on two groups of experiments that we conducted: in subsection 3.2 we present results from one group of experiments, where the pair of attributes were luminance and orientation; in subsection 3.3 we discuss a preliminary study with a second group of experiments with the pair of orientation and luminance-polarity.

3.2 The role of orientation and luminance in texture perception

Two values were assigned to each attribute, as follows: *orientation* - 0 degrees (horizontal bars) and 90 degrees (vertical bars); *luminance* - L_o (dim bars) and L_1 (bright bars). Each bar was formed by the conjunction of the two attributes, and the bars were arranged in the manner indicated in Figure 3, with the following exceptions: the background was black, not gray; the elements shown as black or white in Figure 3 were assigned L_o or L_1, respectively, in the experiments discussed here.

Two subgroups of experiments were conducted, with $L_1 > L_o$ always. In the first one, the ratio of L_1/L_o was set at 2 (L_o = 28cd/m^2; L_1 = 56cd/m^2); in the second subgroup L_1/L_o was set at 4 (L_o = 22cd/m^2; L_1 = 88cd/m^2). One expects that, the smaller the ratio L_1/L_o, the weaker the effect of luminance in forming textural grouping. At the same time, as L_1/L_o becomes smaller, one expects orientation to become stronger in forming texture *across* luminance. Indeed, in the limiting case, as L_1/L_o approaches 1, luminance cannot form patterns since it is uniform throughout the image. Also, when L_1 approaches L_o, matching orientation *across* luminance is equivalent to matching orientation *within* luminance. The reason we tried two values of L_1/L_o was to investigate how this ratio affected the observers' performance.

Within each subgroup in which L_1/L_o was held constant, we tried three types of stimuli: a) luminance across orientation, b) orientation within luminance, and c) orientation across luminance. The results of these experiments are shown in Figure 4, separately for each author, who were the observers, and they are indicated by circles, open squares and filled squares for types a, b and c above, respectively. These results agree with the expected behavior outlined in the previous paragraph. With L_1/L_o = 2, orientation is almost as strong in forming textural patterns *within* luminance as it is *across* luminance, and it is definitely stronger than luminance. When L_1/L_o = 4, however, the superiority of luminance is evident, especially for observer AG, for whom it is also clear that orientation matching across luminance is now much weaker than within luminance. The same trend is also present for observer TVP, although such a clear effect as for AG would probably occur at a higher L_1/L_o ratio.

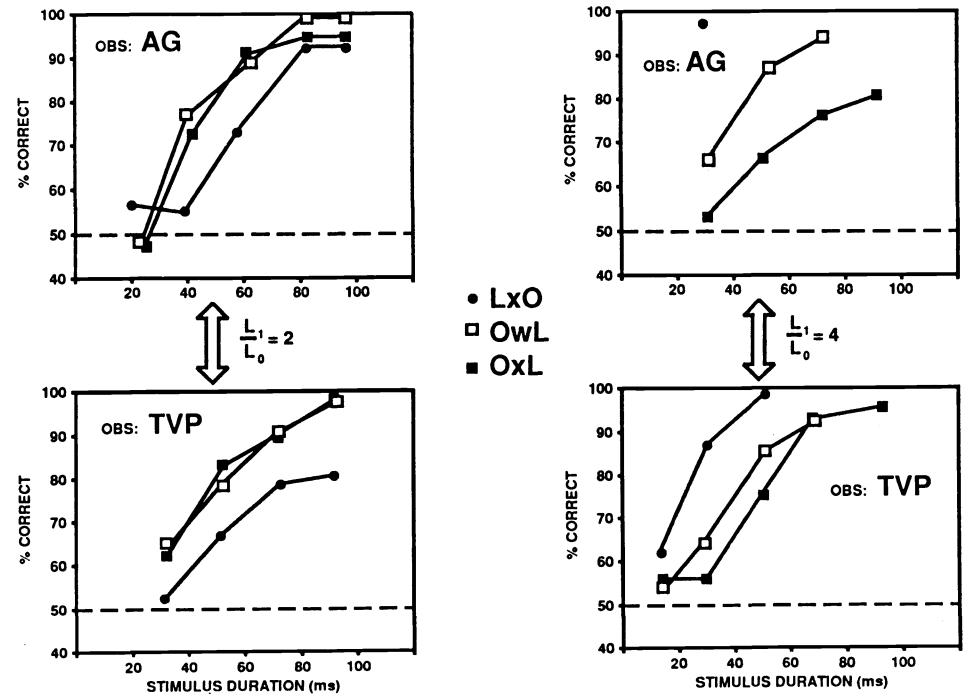

Figure 4: Results of experiments with luminance and orientation. *Top panels*: Observer AG; *Bottom panels*: Observer TVP; *Left panels*: Ratio L_1/L_o = 2; *Right panels*: L_1/L_o = 4. *Filled circles*: Luminance across orientation; *Open squares*: Orientation within luminance; *Filled squares*: Orientation across luminance.

The important observation in all these data is that, even with a luminance ratio L_1/L_o as high as 4, observers are able to perceive textural grouping due to orientation matching across luminance at respectable percent correct rates (higher than 75%), even for low stimulus durations (less than 70ms). This is to be contrasted with the very low performances of orientation matching across luminance-polarity (see next subsection) or across color.[24]

3.3 The role of orientation and luminance-polarity in texture perception.

In this case, one attribute of the textels was orientation, as in subsection 3.2, which was assigned the same two values: 0 degrees and 90 degrees. The other attribute was luminance-polarity: one value was bright green, the other was black, while the green background was of medium intensity; this is shown in Figure 3 with gray substituting for green. For brevity's sake, we shall refer to the second attribute simply as *polarity*. Four types of stimuli were generated and tried in this group: a) polarity within orientation (marked PwO on Figure 5), b) polarity across orientation (PxO), c) orientation within polarity (OwP), and d) orientation across polarity (OxP).

The results of these experiments for observer TVP are shown in Figure 5 with open and filled circles for types a and b above (perfect performance) and open and filled squares for types c and d, respectively. The most striking observation in this group of experiments is that, although orientation matching *within* polarity produces excellent performances, it does vary poorly *across* polarity.

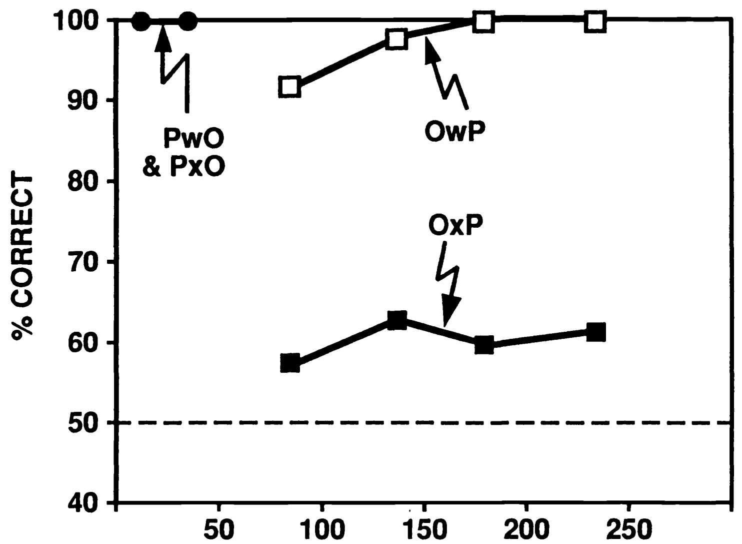

Figure 5: Results with polarity and orientation for observer TVP. The x- and y-axes are as in Figure 4. *Filled circles*: Polarity across orientation; *Open squares*: Orientation within polarity; *Filled squares*: Orientation across polarity.

This suggests once more the concept of a *veto* attribute[26] for texture grouping: an attribute (such as polarity here) which does not allow the matching of another attribute (in this case, orientation) to form textural patterns across it. It seems that luminance *is not* such a veto attribute when combined with orientation, but an earlier study[24] suggests that color *is* another veto attribute for orientation.

4. ISOLATION OF TEXTURE MECHANISMS

To illustrate how this class of texture stimuli can be used to isolate specific mechanisms that are supposedly present in the visual system, let us consider two types of stimuli: a) color within orientation (CwO) and b) color across orientation (CxO). Stimulus CwO activates color mechanisms that are tuned to the particular fixed orientation, i.e. it activates chromatic, orientation-specific pathways; on the other hand, stimulus CxO cannot activate such mechanisms, since multiple orientation values are present. Both stimuli (CwO and CxO) activate color mechanisms that are not tuned to any orientation. Based on these observations, we obtain the following:

Stimulus Type	Mechanisms Activated by Stimulus	
CwO	Chromatic, orientation-specific	Chromatic, orientation non-specific
CxO		Chromatic, orientation non-specific

Thus, the performance with stimulus CxO will activate only the chromatic, orientation-non-specific mechanisms, enabling us to isolate it *directly*. As can be expected from the above Table, the difference in performance in experiments with CwO and CxO will allow us to estimate *indirectly* the activation of the orientation-tuned mechanisms.

5. SUMMARY - CONCLUSIONS

The class of stimuli presented here allow one to combine an arbitrary number of attributes in independent ways for forming textural patterns. The main advantages are: a) the *interaction* of attributes becomes possible to be studied; b) the relative strength of two attributes in forming textures can be compared *directly* by a stimulus in which the two are matched competitively (subsection 2.3); c) specific visual mechanisms can be isolated by proper choice of stimuli.

The results of two groups of experiments, one involving luminance and orientation, the other involving polarity and orientation, were presented. It appears that polarity acts as a veto attribute for orientation (subsection 3.3), whereas luminance does not. There is a certain similarity between these results and earlier results in motion perception,[26] suggesting that mechanisms processing 2-D spatial information (x-y texture) act similarly to those processing spatio-temporal information (x-t motion). Additional experiments are required to investigate further such apparent similarities.

Finally, it is worth noting that results from experiments in texture perception with stimuli that allow multiple attributes to participate in the process, such as the ones presented here, will be very useful for extending recent filter-based models for automatic texture segregation[27-31] to cover the multitude of attributes that the human visual system is able to handle.

6. ACKNOWLEDGMENTS

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