A note about preferred orientations at the first and second stages of complex (second-order) texture channels

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Complex (second-order) channels have been useful in explaining many of the phenomena of perceived texture segregation. These channels contain two stages of linear filtering with an intermediate pointwise nonlinearity. One unanswered question about these hypothetical channels is that of the relationship between the preferred orientations of the two stages of filtering. Is a particular orientation at the second stage equally likely to occur with all orientations at the first stage, or is there a bias in the "mapping" between the two stages' preferred orientations? In this study we consider two possible mappings: that where the orientations at the two stages are identical (called "consistent" here) and that where the orientations at the two stages are perpendicular ("inconsistent"). We explore these mappings using a texture-segregation task with textures composed of arrangements of grating-patch elements. The results imply that, to explain perceived texture segregation, complex channels with a consistent orientation mapping must be either somewhat more prevalent or more effective than those with an inconsistent mapping.

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1. INTRODUCTION

Structures like those in Fig. 1—in which big receptive fields at a second stage "paste together" the (nonlinearly transformed) outputs of little receptive fields at the first stage—have been suggested to underlie a variety of perceptual phenomena. We call these structures, as they act in texture-segregation tasks, "complex channels." This term was inspired by Robson's suggestion that complex cortical cells could perform such perceptual tasks,[1] but the possible analogy to physiology should be taken with care. (For further discussion, see p. 732 top, of Ref. 2 and Appendix, part I, of Ref. 3.) Such structures have also been called "second-order" or "non-Fourier" mechanisms, "sandwich" or "linear–nonlinear–linear" structures, "collator" or "collector" units, and a variety of other names. A brief review of many such suggestions can be found in Ref. 3.

We now know some of the properties of these structures necessary to explain at least some perceptual tasks, but a wide variety of questions about their properties remain open. For the hypothetical complex channels subserving texture segregation, the study here addresses the question that is illustrated in the top and bottom of Fig. 1. What is the relationship between the preferred orientation of the first-stage receptive fields and that of the second-stage receptive fields in complex channels? Is a particular orientation at the second stage equally likely to occur with all orientations at the first stage, or is there a bias in the "mapping" between the two stages' preferred orientations? (We already know that the first stage of most if not all complex channels is orientation selective.[4,5]) The two possible relationships illustrated in Fig. 1 have been of particular interest and are the ones considered here. Perhaps, for example, there is a tendency for the orientations at the two stages to be perpendicular, as shown in the top of Fig. 1. This relationship has been suggested by Wilson, Wilkinson, and colleagues for discriminating curvature at texture boundaries,[6] for detecting the global structure of concentric Glass patterns,[7] and for the detection and recognition of a class of smooth closed shapes potentially including many natural forms such as faces and fruits.[8] Or perhaps there is a tendency for the orientations at the two stages to be the same (as in the bottom of Fig. 1), which means that the little receptive fields of the first stage are parallel to the big receptive fields of the second stage. This relationship would increase the salience of smooth contours by producing facilitation between contour segments of identical or similar orientation. This kind of process has been suggested in explaining results from the series of studies originating with Field *et al.*[9] and Polat and Sagi.[10,11] This is also the relationship suggested for detecting the global structure of radial Glass patterns.[12] For ease of referring to the two particular relationships illustrated in Fig. 1 we will call them inconsistent (when the orientations at the two stages are perpendicular) and consistent (when the orientations at the two stages are the same). Many other arrangements are, of course, possible, but they will not be directly studied in the experiments reported here.

2. THIS STUDY

To answer the question of whether there is a bias toward consistent or inconsistent orientation mapping in the complex channels involved in texture segregation, we use texture patterns like those in Fig. 2. Each pattern contains two regions: a rectangle and a surround. One region contains a checkerboard arrangement of elements, and the other contains a striped arrangement. In Fig.

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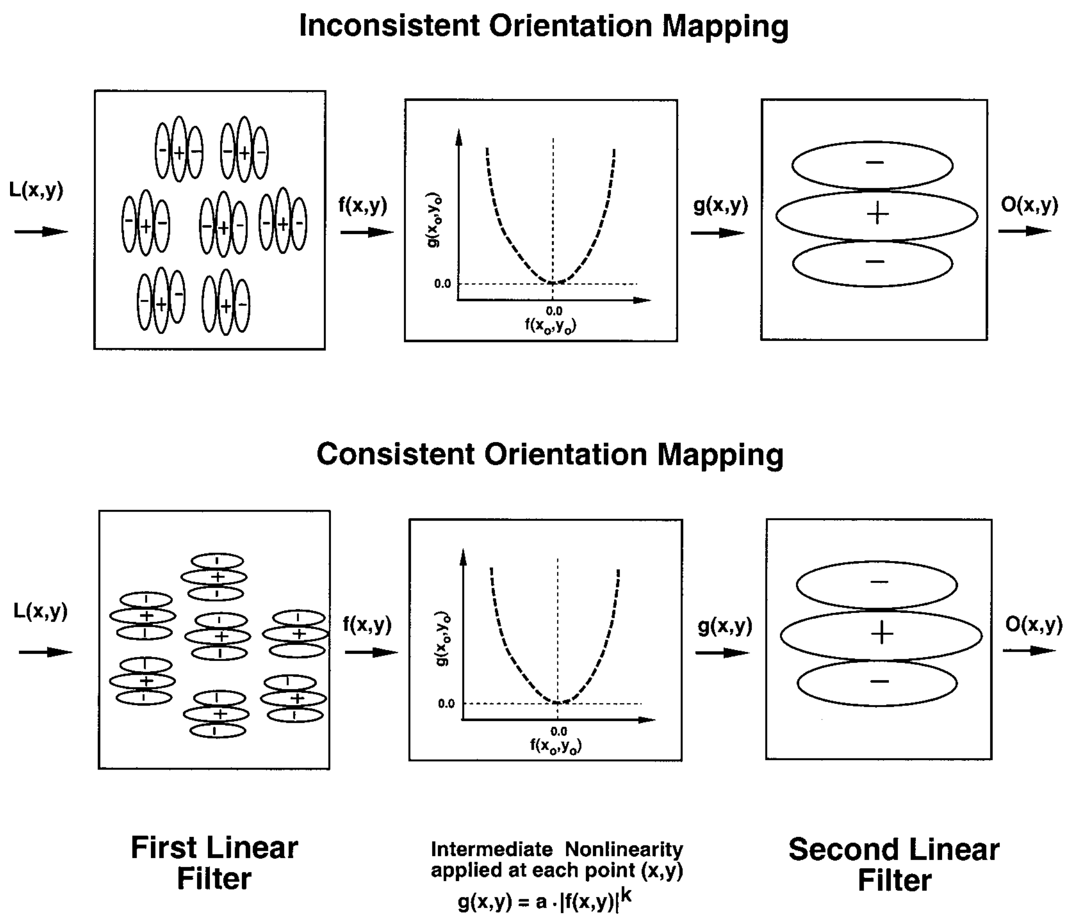


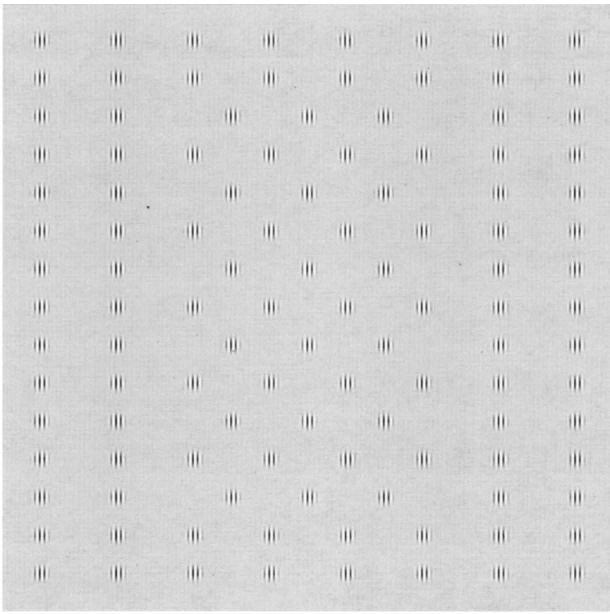
Fig. 1. Diagrams showing complex channels involved in the perceived segregation of texture regions.[2,13,14] The first-stage filter is known to be orientation selective[5] and spatial-frequency selective.[4] The intermediate stage in the complex channels is known[3] to be expansive with an exponent k of approximately 3 or 4. The question of orientation mapping—how the preferred orientations at the first and second-stage filters are related—has not been answered. Here we study two possible mappings: "inconsistent," where the orientations at the two stages are perpendicular (top row), and "consistent," where the orientations at the two stages are parallel (bottom row).

2(a) the rectangle is a checkerboard pattern and the surrounding texture is striped. In Fig. 2(b) the reverse is true. These are a subclass of the more general class of element-arrangement textures that we have used in a wide variety of tasks. Ordinarily these patterns contain regions made up of different arrangements of two kinds of elements (see, e.g., Ref. 13). Here, however, only one kind of element is visible, as the contrast of the other has been set at zero. These patterns are very similar to modulated noise patterns: The grating patches here are the carrier (but they are a deterministic rather than noisy carrier), and the arrangement into stripes or checkerboard is produced by the modulator. The task of the observer in this study is to say whether the embedded rectangle is horizontally elongated [Fig. 2(b)] or vertically elongated [Fig. 2(a)], where the exact positions of the rectangles vary from trial to trial.

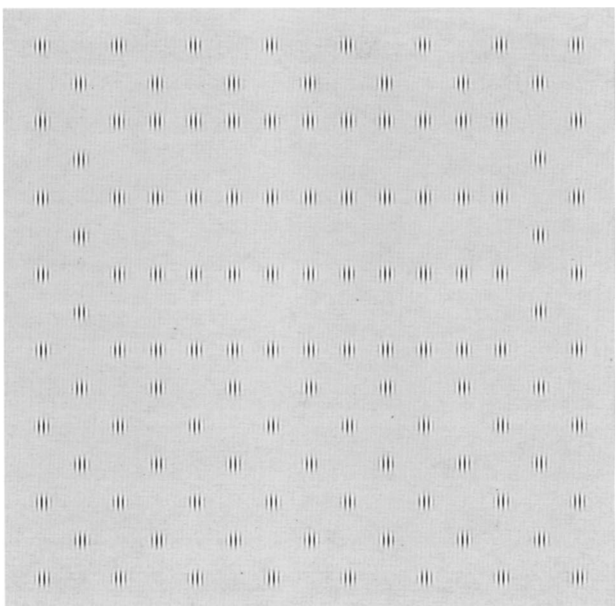
Sometimes the orientation of the stripes in the striped arrangement (whether they be in the rectangle or in the surround) and the orientation of the grating elements making up those stripes are identical, as in Fig. 2(a). We will refer to these patterns as having a "consistent" orientation mapping. Sometimes, as in Fig. 2(b), the orientation of the stripes themselves is perpendicular to the orientation of the grating elements. We will refer to these patterns as having an "inconsistent" orientation mapping.

An observer's ability to segregate these patterns can tell us whether the orientation mapping between the first and second stages (of the complex channels involved in this task) is biased toward consistent or inconsistent. As we will describe briefly, Fig. 3 illustrates the results to be expected given each kind of orientation mapping. (To write out the full explanation in detail would take more space than seems appropriate here. The full explanation is analogous to those written out in more detail for Fig. 11 in Ref. 2 and Fig. 6 in Ref. 3, to which the interested reader can refer.)

The two kinds of patterns that we used are indicated at the top of Fig. 3 by showing a small portion of the striped texture region. The two possibilities for channel structure are indicated on the right side of Fig. 3 in a more condensed form than in Fig. 1. (In this condensed form, the little receptive fields of the first-stage filter are shown superimposed on the big receptive field of the second filter. The intermediate nonlinearity is not represented.) The gray-level images in the interior of Fig. 3 illustrate the outputs immediately after the intermediate nonlinearity (before the second-stage filter) of the complex channel. The brightest points in the gray-level images indicate the maximal responses, the darkest points the minimal. Superimposed on these gray-level images are sketches of the receptive field of the second-stage filter. The final output



(a)



(b)

Fig. 2. Stimulus examples with vertical elements. (a) Consistent pattern, in the background. Outside the rectangle the pattern is vertical stripes and the elements are vertical. Inside the rectangle the pattern is checkered. The rectangle is in the middle position oriented vertically. The phases of each element are identical (positive sine phase) so this is a constant-phase pattern. (b) Inconsistent pattern, inside the rectangle. In the rectangle the pattern is horizontal stripes and the elements are vertical. Outside the rectangle the pattern is checkered. The rectangle is in the top position oriented horizontally. The phase of each element is randomly chosen to be either positive-sine- or negative-sine phase, so this is a random-phase pattern. All the mentioned factors (horizontal versus vertical element orientation, consistent versus inconsistent stripe orientation, stripes outside versus inside the rectangle, rectangle oriented horizontally versus vertically, three positions of rectangle, constant phase versus random phase) were counterbalanced in the set of patterns used in the experiments here.

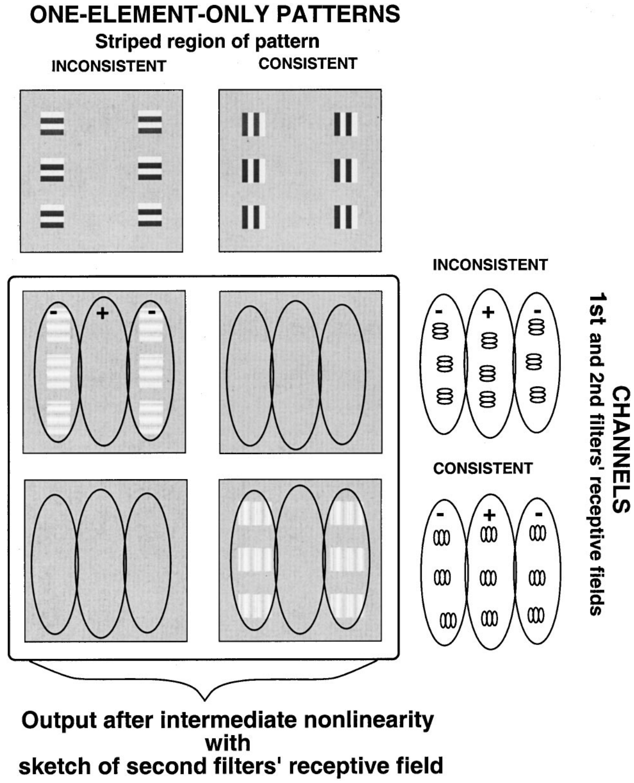


Fig. 3. At the top, small portions from the striped regions of two patterns are shown. On the right, channels with inconsistent and consistent orientation mapping are schematically indicated. Each gray-level image in the interior shows the complex channel's output immediately after the intermediate nonlinearity (before the second-stage filter); the brightest points indicate the maximal responses and the darkest points the minimal. Superimposed on these gray-level images are sketches of the receptive field of the second-stage filter to help in deducing the final output of the complex channel (the output after the second-stage filter). As can be deduced, this final output in the striped region will be modulated only when the orientation condition in the channel matches that in the striped region of the pattern.

of the complex channel (the output after the second-stage filter) can easily be deduced. There will be a modulated final output only when the orientation mapping in the channels (consistent or inconsistent) matches that in the striped region. (The outputs in the checkerboard region will not depend on whether the orientation mapping is consistent or inconsistent. Also, the particular details of the assumed comparison-and-decision stage will matter very little, at least within the large family of rules that we routinely investigate.) Thus, within the framework of a very large class of models, an observer is predicted to be able to segregate the striped region from the checkerboard region if and only if the orientation mapping in the complex channels matches that in the pattern's striped region.

One further point deserves special remark. In Fig. 3, the grating-patch elements are assumed far enough apart that no receptive field in the first-stage filter responds significantly to more than one element. Therefore in this study we have spaced the elements very widely. Further, we use not only patterns in which all the grating patches are in the same phase and thus aligned [Fig. 2(a)] but also patterns in which the grating patches' phases are randomly selected from the positive-sine and negative-sine phases [Fig. 2(b)]. The wide spacing and random phase are used in order to unambiguously draw conclusions from this experiment about the orientation mapping between first and second filters. Otherwise, any differences between performance on consistent and inconsistent patterns might be due to properties of the first-stage filter's receptive field. For example, receptive fields at the first-stage filter that were elongated more in one direction (e.g., parallel to their regions) than in the perpendicular direction could produce an advantage for consistent over inconsistent patterns by summing over more elements in the first direction.

It is easy to demonstrate casually that observers can segregate both inconsistent and consistent patterns. However, the question of whether channels of the two configurations are equally effective requires more careful data collection. In the experiments reported here, patterns with consistent orientation mapping are found to be somewhat easier to segregate than those with inconsistent orientation mapping. Within the context of our theoretical framework, this implies that complex channels in which the receptive fields at the first and second stages have the same orientation are more prevalent or more effective than those with perpendicular orientations at the two stages.

3. DETAILS OF METHODS

Stimuli were presented on an Apple 17-in. ColorSync monitor (75 Hz refresh rate, 1280×1024 resolution) controlled by a Power Mac G3. The mean luminance of our patterns was approximately 20 cd/m^2. Stimuli were generated and presented by using Math Works' MATLAB with the Psychophysics Toolbox extensions.[15,16] The monitor's lookup table was linearized. Subjects were in a dimly lit room.

Each stimulus contained 15×15 Gabor-patch elements. The embedded rectangle contained 7×11 elements. When vertically elongated, the rectangle could occur randomly in any of three overlapping positions: left of center, center [as in Fig. 2(a)] and right of center. When horizontally elongated, it could occur randomly in any of three positions: top [as in Fig. 2(b)], center, and bottom. The random assignment of rectangle position diminishes the probability that the observer can do the task by attending to a very few elements at a fixed location.

In half of the patterns the rectangle contained the checkerboard arrangement of elements and the background contained the striped arrangement (which was vertical or horizontal with equal probability). In the other half of the patterns, the rectangle was striped (horizontal or vertical) and the background was a checkerboard.

For three observers the viewing distance, with unrestrained head, was approximately 43 cm, and for the other two observers it was approximately 86 cm.

Each element was truncated to lie within a square of width 64 pixels so that neighboring elements did not overlap. (Sixty-four pixels subtends 1 deg at a viewing distance of 86 cm, and 2 deg at 43 cm.) The period of the sinusoid in each Gabor patch (to be called λ) was 8 pixels, so the spatial frequency was 1/8 cycle per pixel, which was 8 cycles per degree (c/deg) at a viewing distance of 86 cm and 4 c/deg at 43 cm; the grating-patch orientation was either vertical or horizontal. The full width at half-height of the circular Gaussian envelope of each Gabor patch (W) was 16 pixels (0.25 deg at a viewing distance of 86 cm, 0.5 deg at 43 cm), which equals 2λ (2 periods of the sinusoid). The center-to-center distance between the Gabor patches (D) was 64 pixels, which equals 8λ (8 periods of the sinusoid). The "blank" space between the patches (the distance over which both patches are at less than half-amplitude) equals $D - W = 6\lambda$. Or, being even more conservative, the "empty" space between the patches (the distance over which both patches are at less than 7% of their peak height) equals $D - 2W = 4\lambda$.

Two phase conditions were investigated. In the constant-phase condition, the phase in the Gabor patch (the phase of the harmonic oscillation in the Gabor-patch elements) was in positive-sine phase with respect to the window (so that the space-average luminance was always the same as the background luminance). In the random-phase experiments, the phase in each element was randomly chosen from two possibilities, either positive-sine phase or negative-sine phase [as can be seen by scrutinizing Fig. 2(b)].

The period at which either the checked or the striped arrangement repeats itself is 128 pixels (two elements). Thus the fundamental frequency of the element-arrangement patterns was 1/128 cycles per pixel (0.5 c/deg at a viewing distance of 86 cm and 0.25 c/deg at a viewing distance of 43 cm).

These element-arrangement patterns are analogous to the modulated-noise patterns used by a number of other investigators. The frequency and orientation in the Gabor patches here are analogous to the carrier frequency and orientation, and the fundamental frequency here is analogous to the modulation frequency.

The patterns were presented for 100 ms with abrupt onsets and offsets.

The patterns could occur at three contrasts, which were different for different observers, as were the viewing distances (see figure labels). The values were chosen on the basis of pilot experiments to produce performance greater than chance and less than ceiling.

The subject's task in the experiment was to indicate the orientation of the embedded rectangle. To begin each trial, the observer pressed the "0" key (on the numeric keypad) which presented a fixation point (a low-contrast 20×20 pixel square) for 500 ms followed by a screen that was uniform at the mean luminance for 500 ms. Then the stimulus appeared for 100 ms, with abrupt onset and offset, followed by a uniform screen until the observer responded. The observer was forced to wait 1 s after the stimulus terminated before responding (the computer beeped to indicate when the observer could respond), a procedure that we initiated to make sure that observers waited for appropriate processing before responding,[4] which is particularly important when complex channels are involved, as they are rather slow.[17,18] The observers then pushed either the "8" key on the numeric keypad to indicate that the rectangle was vertical or the "4" key to indicate that the rectangle was horizontal. A high- or low-pitched tone provided feedback as to the correctness of the response.

Each session consisted of 432 trials, 144 at each of three contrasts. Either all patterns in a given session were of constant phase or all patterns in a given session were of random phase. Forty-eight of the 144 trials at a given contrast presented patterns containing both vertical and horizontal elements, and they will not be considered further here. The remaining 96 trials at each contrast consisted of all combinations of (i) the position and elongation of the rectangle (six possibilities), (ii) the characteristics of the striped arrangement (either in rectangle or in surround, and either horizontal or vertical stripes, therefore four possibilities), (iii) the orientation of the elements, which in combination with the orientation of the stripes determined whether it was consistent or inconsistent (two possibilities), and (iv) whether the upper-left element position was blank or filled (two possibilities).

Each observer participated in five sessions with the constant-phase patterns and subsequently in five sessions with the random-phase patterns.

There were five observers, two of whom were the authors. The others were paid undergraduates with no previous experience in texture experiments (although AF and MK had extensive experience in light-adaptation experiments). All observers participated in pilot conditions. All observers had normal or corrected-to-normal visual acuity.

4. RESULTS

Figure 4 shows the results of the constant-phase experiments for the five observers (five rows). The columns show the results for patterns where the striped texture arrangement was inside the rectangle (left column) or outside the rectangle (right column). Each panel shows the results as a function of contrast, where the symbols show the probability of correct response for consistent (solid symbols) and inconsistent (open symbols) patterns. (Each data point in the figure shows the mean performance over five sessions, with ± one standard error of the mean. The performance in each session is the proportion correct on 48 trials.)

In all cases, performance for consistent and inconsistent patterns is quite similar but is systematically higher for the consistent case (except where near chance or near ceiling). This is true whether the striped region was inside the rectangle (left column) or outside the rectangle (right column). The exact difference in performance may depend to some extent on the observer. Although not shown explicitly in the figure, consistent patterns produce better performance than inconsistent patterns regardless of whether the stripes, the individual elements, or the rectangles are horizontal or vertical.

Although there are too few points in each curve in Fig. 4 to make a strong statement, it will be convenient to speak as if the curves for the consistent and inconsistent orientation-mapping patterns were horizontal translations of one another on the log contrast axis. This will allow us to express the difference between performance on the consistent and inconsistent patterns in terms of contrast. To make the curves for consistent and inconsistent patterns superimpose, one could ask how much the curve for the inconsistent case has to be translated to the left. We estimated this factor using very simple interpolations near the middle of the curves. This yielded factors substantially less than an octave (less than a factor of 2) in almost all cases. For the ten panels in Fig. 4, the factor has a median value of approximately 8/20ths of an octave on a log scale (a factor of approximately 1.32 on a linear scale) with a substantial amount of variation from panel to panel.

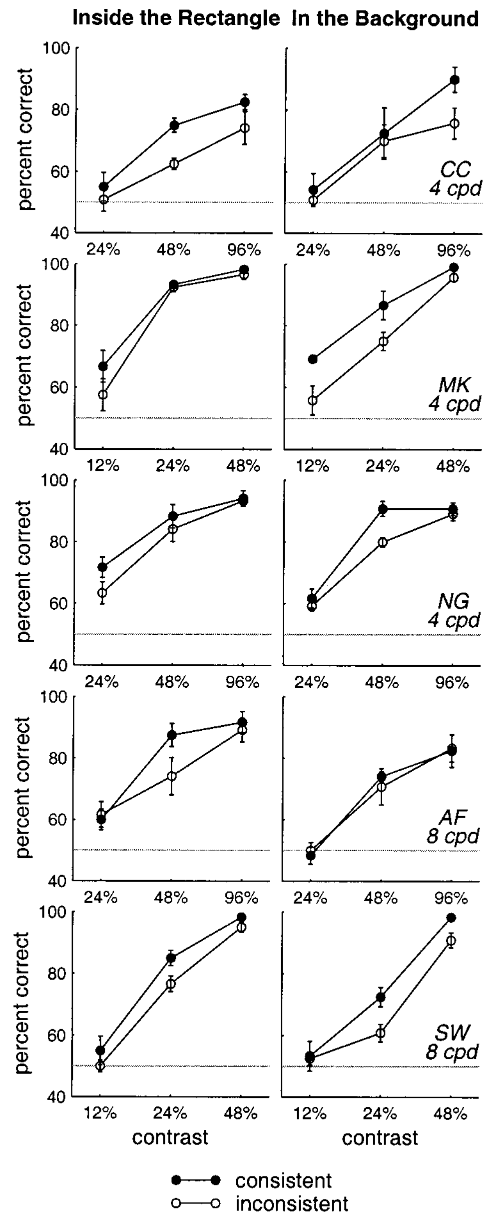


Fig. 4. Results of the experiments with constant-phase patterns for five observers. The left (respectively, right) panel for an individual observer shows the results for patterns where the striped texture arrangement was inside (respectively, outside) the rectangle. Each panel shows the results as a function of contrast, where the solid and the open symbols show the probability of correct response for consistent and inconsistent patterns, respectively. (Each data point in the figure shows the mean performance over 5 sessions, where the performance in each session was the proportion correct on 48 trials. The error bars show ± 1 standard error of that mean.) cpd, cycles per degree.

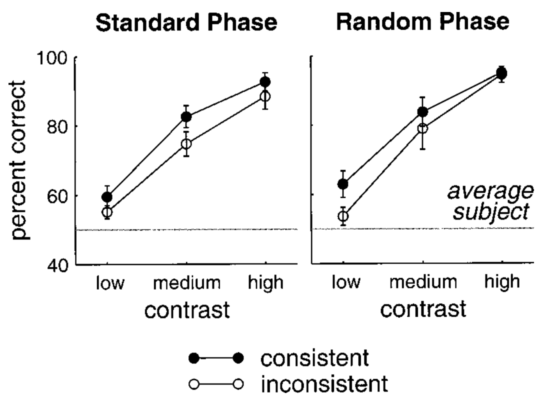


Fig. 5. Performance in the constant-phase experiments (left panel) and the random-phase experiments (right panel). Each panel shows the averages over the five observers and also averages over the cases in which the striped regions were inside or outside the rectangle. The left panel shows the average of all ten panels in Fig. 4. The error bars show ± 1 standard error (computed over observers).

Figure 5 summarizes the performance in the random-phase experiment in comparison with the constant-phase experiment. The left panel shows the results averaged over the ten panels of Fig. 4, and the right panel shows the results averaged over the analogous cases in the random-phase experiment. (The same observers, at the same viewing distances and contrasts, participated in both experiments; the random-phase sessions were all run after the constant-phase sessions.) The advantage in performance for consistent over inconsistent patterns held when phase was randomized, as it had when phase was unrandomized, and seemed to be the same magnitude within measurement error. In the random-phase results, the median factor by which one would have to translate the curve for the inconsistent case to the left to produce superposition was approximately 7/20ths of an octave on a log scale (a factor of 1.27), compared to the median of approximately 8/20ths of an octave (a factor of 1.32) for the constant-phase case of Fig. 4. (These are not significantly different.)

5. DISCUSSION

Our results (Figs. 4 and 5) can be explained by assuming that complex channels with a consistent orientation mapping (receptive fields of the same orientation at the two stages) are either more prevalent or more effective than those with an inconsistent orientation mapping (receptive fields of perpendicular orientations at the two stages). Putting this in terms of stimulus contrast, the difference in effectiveness can be canceled by raising the contrast in the inconsistent patterns—and therefore raising the input to the inconsistent complex channels—by a factor that differs from observer to observer but is always much less than 2 with a median value of approximately 1.3.

A. Considering Alternative Explanations

In this section we first consider several alternative explanations for the results here that can be ruled out or at least tentatively dismissed as unlikely. Then we discuss a more general set of alternative explanations that cannot be ruled out.

1. *Alternatives That Seem Unlikely*

First-stage receptive field properties. An alternative explanation based on elongated receptive fields at the first stage of the complex channels does not seem tenable for the results here. There is, however, no way to completely rule out the receptive-field argument unless one agrees on what other empirical results should be allowed to constrain those receptive fields (cf. Ref. 19). We think that the individual grating-patch elements in the patterns here were so far apart that no receptive field at the first stage of the complex channels should have been stimulated to a significant extent by more than one patch, at least not if the receptive fields have characteristics like those commonly thought to underlie spatial vision (e.g., see review in Refs. 20 and 21). Further, randomizing the phase of the grating patches did not decrease the advantage of consistent over inconsistent although such randomization makes the patches that could stimulate the same receptive field even farther apart on average.

Nontuned complex channels. Another complication that should be raised is whether "other" complex channels (other than those explicitly considered here) may contribute significantly to the observers' responses, even perhaps to the extent of producing the advantage for consistent patterns. The channels in Fig. 3 are those that are tuned to the spatial frequencies and orientations of the elements and of the arrangements of the patterns we used. The "other" channels would be those sensitive to other spatial frequencies and orientations. Most of these "other" channels, if they were stimulated, would actually diminish the effect of different orientation mappings. In any case, since our elements contain a relatively narrow range of spatial frequencies and orientations and are also widely spaced, these "other" channels are not substantially stimulated by our patterns.

Intensive nonlinearities. In interpreting the results of these experiments in terms of one kind of nonlinearity—complex (second-order) channels—the question should be considered of whether other types of nonlinearities in the visual system might affect the interpretation. For one thing, to explain perceived texture-segregation results, the transformation at the intermediate stage in the complex channels must be somewhat more complicated than an ordinary rectification; instead, it is well described as a pointwise expansive power function[3] with an exponent k of 3 or 4. This expansive pointwise nonlinearity will not affect relative performance here because consistent and inconsistent patterns contain identical elements, and this nonlinearity has its effect pointwise and thus on individual elements.

Second, any early nonlinearity coming before the channels and acting locally (e.g., retinal light adaptation or transformations at the lateral geniculate nucleus) should not affect relative performance on consistent and inconsistent patterns and thus does not affect the conclusion here.

Finally, to explain perceived texture-segregation results, an extremely compressive intensive nonlinearity has been demonstrated that can be explained as the result of interchannel inhibition in a normalization network.[14,22] Some consideration shows that this type of normalization network will not affect relative performance on consistent versus inconsistent patterns (unless there is something very asymmetric about which channels enter the normalization pools for consistently versus inconsistently mapped channels.)

2. Alternatives That Make Similar Predictions

The results explained by complex channels here may be better explained eventually by an entirely different theoretical framework. This caveat is true for all results, of course, but may be particularly relevant here.

A kind of theoretical framework that may be seen as different enough to merit separate discussion here (while not being entirely different) is one in which in-place dynamic lateral interactions are assumed to exist among one level of receptive fields (e.g., the first-stage receptive fields) before that stage feeds into higher levels of receptive fields. Such lateral interactions have been extensively investigated physiologically and anatomically (see brief review in Ref. 23), and they have been used in many explanations of perceptual phenomena: for example, the linking process of Beck and his colleagues,[24,25] the cooperative grouping algorithms of Zucker,[26] the impletion process of Caelli,[27] the cooperation processes of Grossberg and Mingolla,[28] the active reentrant connections of Sporns *et al.*,[29] the in-place spatial interactions of Polat and Sagi,[10,11] the association field of Field *et al.*,[9] and the excitatory and inhibitory lateral interconnections among pyramidal cells in the computational model of Li.[30]

Within the framework of theories assuming lateral interactions, the empirical results here could be interpreted by postulating excitatory lateral interactions among nearby but nonoverlapping first-stage receptive fields responding to the same orientation and aligned end to end (while not postulating such facilitation for other first-stage receptive fields) as in the models of, for example, Grossberg and Mingolla[28] by Zucker[26] and Li.[30]

The explanation just given in terms of lateral interactions among receptive fields at the same level sounds rather different from the explanation given above in terms of different mappings of orientations between the first and second stages of complex channels (Fig. 3 here). For the empirical results here, however—and for many results, in fact—these theoretical frameworks make the same predictions and are therefore indistinguishable.

B. Comparison with Other Studies

Several previous studies, discussed below, have explored the effects of consistent and inconsistent mappings between the orientation of local elements in the pattern and the orientation of more global aspects. These studies' results are generally in accord with the results here. In these previous studies, however, there is less "blank" space between local elements and thus more likelihood that characteristics of first-stage receptive fields (rather than the relationship between preferred orientations at first and second stages of any hypothetical mechanism or process) explain their results.

Two studies, both involving separated Gabor-patch elements, showed that consistent orientation mapping produces better performance than inconsistent orientation mapping. One task[9] involves finding a contour of elements in a background of noise elements (see also Ref. 31), and the other task[11] is the detection of a target patch in the presence of flanking masks.

Using modulated-noise patterns with a detection-of-modulation task[32,33] produces very little effect of inconsistent versus consistent orientation mapping in the conditions most similar to those here; however, one of the two subjects in Ref. 32 (Fig. 8, lower right panel, carrier frequency 8 c/deg and modulation frequency 0.35 c/deg) shows a slightly greater sensitivity for the consistent than for the inconsistent condition. With much lower carrier frequencies (that are much nearer to the modulation frequency) the results are opposite to the results here; that is, they show a clear advantage for the inconsistent patterns.[32] But interpreting the results when the modulation and carrier frequencies are close is difficult because simple (linear, first-order) mechanisms can also do the task.

A study measuring an observer's ability to discriminate straight from wavy texture edges (with textures made up of multiple oriented lines) found a pattern of evidence[34] suggesting that the second-stage filters involved in signaling the presence of a texture edge were biased toward the consistent orientation mapping (they weighted first-stage filters of the same orientation as the second-stage filter more heavily than those of other orientations). Similarly, detection of an embedded region of oriented lines is superior when the lines align with the outline of the figure.[35]

In general, one could ask a broader question than we have asked here—one could ask about other possible mappings of the orientations at the two stages of complex channels. Two of the studies[11,34] mentioned above and also a study on texture segregation with element-arrangement textures[18] provide a hint about the case in which oblique first-stage receptive fields are connected to vertical or horizontal second-stage receptive fields. These three studies suggest that the oblique case is less effective than the consistent or the inconsistent mappings studied here (although caution is again warranted since their elements were close together and thus multiple elements might stimulate the same first-stage receptive field).

Little physiological or anatomical evidence is available that bears directly on complex channels or second-order processing. In single cells of area 18 of the cat, which do some non-Fourier (complex-channel-like) processing, the neurons' optimal carrier (first-stage) orientation was not systematically related to the envelope (second-stage) orientation.[36] It is not clear, however, that the physiological study would have revealed an effect as small as that necessary to underlie the psychophysical results here.

More information is available on the general topic of lateral interactions among neurons in area V1. And indeed there is a tendency for finding the greatest interactions when receptive fields are aligned as in the consistent case here. However, it is unclear that the dominant interaction should be excitatory rather than inhibitory. (See brief review in Ref. 23.)

C. Analogous Spatial-Frequency Question

The analogous question about the relationship between preferred spatial frequencies of a complex channel's two stages has also been investigated. There were early suggestions that the preferred spatial frequencies of first-stage and second-stage texture filters might be positively correlated, although the first-stage value would always be expected to be higher than the second.[37,38] Detection of modulation of broadband noise suggests that the first-stage preferred spatial frequency tends to be approximately 8–16 times higher than the second-stage value.[39] Some vernier acuity results have been interpreted in terms of correlated sizes of receptive fields at the first and second stages (with larger second-stage receptive fields being used in conjunction with larger first-stage receptive fields).[40] Results with orientation-modulated textures are also consistent with a correlation in spatial scale at the two stages.[41] However, results with contrast-modulated textures[32] have been used to argue against a fixed relationship between preferred spatial frequencies at the two stages. It is certain that there is *not* a perfect correlation: Using suitable interleaved-contrast-modulated textures produces good evidence that there are multiple channels with different preferred spatial frequencies at the second stage but the same preferred spatial frequency at the first stage.[42,43] Perhaps the fairest conclusion at this point about spatial-frequency mapping is that, if there is a correlation between the preferred spatial frequencies at the two stages of second-order mechanisms, it is small and is a bias toward the preferred spatial frequency of the first filter being several octaves higher than that of the second.

D. Conclusion

For the complex (second-order) channels involved in segregation of the textures used here, those channels with consistent orientation mapping (having receptive fields of the same orientation at the first and second stages) are either somewhat more prevalent or somewhat more effective than those with inconsistent orientation mapping (perpendicular orientations at the two stages). The difference is not great, however, approximately a factor of 1.3, suggesting that both arrangements are of value to the visual system in its effort to make sense of the world.

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