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Preattentive Equivalence of Multicomponent Gabor Textures in the Central and Peripheral Visual Field

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Similarity ratings were obtained to determine the minimum number of Gabor components that would produce a comparison texture that appeared preattentively similar to a 64-component standard texture. All textures were chosen to be both specifiable by a relatively small number of localized spectral components and sufficiently complex to approximate natural textures. The number of component orientations in the set of comparison textures was found to be a particularly important determinant of texture discrimination in that its effect on rated similarity was largely independent of the total number of components making up the texture. Textures were also presented at 0.75° and 20° eccentricity, with the latter magnified by a factor of either 2 or 4. The overall similarity rating did not change with either magnification, whereas the critical number of orientations, defined as the number of orientations above which rated similarity was constant, did change for the higher magnification. The latter finding is consistent with the proposition that higher-order discriminations are mediated by higher cortical areas that integrate information across the visual field. Finally, the phase-bandwidth of a set of coherent textures was also varied in order to determine whether more explicit differences in the spatial structure of stimuli might affect rated similarity. In contrast to the results for component orientation, the ratings, obtained at 0.75° and 20°, were different even when the phase-bandwidth stimuli were magnified by a factor of 4.

Texture discrimination Orientation Phase Gabor functions Eccentricity scaling

INTRODUCTION

At the earliest stages of the visual system, a complex image is represented as activity in a set of visual neurons with relatively simple receptive fields (Braddick, Campbell & Atkinson, 1978; Graham, 1989). Cortical representations are therefore not point-by-point replications of the stimulus, but rather are derived from and are constrained by the characteristics of these receptive fields. It has further been proposed that the visual system may be most sensitive to simple luminance distributions that match the spatial structure of visual receptive fields (Kronauer & Zeevi, 1985; Watson, Barlow & Robson, 1983). If this is the case, it is possible that a complex image can be more efficiently analyzed if its structure is also homologous to the visual receptive field.

Complex images, that well approximate natural textures, can be synthesized from simple spectral components that resemble receptive fields (Porat & Zeevi, 1989). Further, the analysis of natural images (Field, 1987) suggests that a complex texture may be represented by a set of spectral components some of which do not contribute significantly to the appearance of the texture. Such components can in theory be removed without substantially affecting the appearance of the texture, and so these textures may be appropriate stimuli for determining the minimal information required to produce an effective visual stimulus.

While there is no general model of the perception of suprathreshold textures (but cf. Clark & Bovik, 1989; Graham, Beck & Sutter, 1992; Turner, 1986), it might be expected that the properties of the receptive fields mentioned above would be reflected, at least qualitatively, in the perceptual response to more complex images. For instance, two components which are very similar in spatial frequency might interact such that the contribution of the components to the overall appearance of an image would be smaller than that of two components that are separated more widely in spatial frequency. Or assuming that the perception of two-dimensional spatial frequency (i.e. spatial frequency and orientation) is mediated by a relatively small number of overlapping mechanisms, one of these mechanisms could be overstimulated, in the sense

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that adding another component within its bandwidth could result in a relatively smaller change in the mechanism's output and hence an overall smaller perceptual difference in the stimulus. If such interactions occur, then two stimuli can be perceptually equivalent even if they are composed of different numbers of spectral components. An interesting example of a stimulus equivalence class of this type was described by Kronauer, Daugman and Zeevi (1982), who found that as few as 5–6 suitably chosen spectral components can produce a texture that is indistinguishable from bandlimited white noise.

The visual system is spatially inhomogeneous, and therefore it cannot be assumed that equivalence classes are the same at all locations in the visual field. The ability to discriminate both spatial frequency and orientation is known to decrease with retinal eccentricity, and this decrease can be compensated by magnifying the stimulus (Rovamo, Virsu & Näsänen, 1978; Scobey, 1982; Nothdurft, 1985; Johnston, 1987). However, other stimulus characteristics that might appear related to spatial frequency and orientation are often processed differently. For instance, Nothdurft (1985) found that the minimum line orientation that could be discriminated was generally smaller than the orientation difference required to discriminate adjacent textures. Also, Scobey (1982) estimated the magnification required to equate line orientation discrimination at different eccentricities to be less than one-half that estimated by Paradiso and Carney (1988) for a similar task. Thus, given that more than one component process may be involved in discriminating complex stimuli, and given that more complex discriminations may be mediated by higher (and progressively more integrative) cortical areas (cf. Gattass, Sousa & Covey, 1985; Levi, Klein & Aitsebaomo, 1985), it might be expected that simple and complex stimuli would have to be magnified differently in order for them to appear the same at different eccentricities.

The scaling factors that have been estimated for certain positional judgments such as vernier acuity (Klein & Levi, 1987; Levi *et al.*, 1985) and phase discrimination (Bennett & Banks, 1991; Rentschler & Treutwein, 1985) are typically greater than for simple luminance or contrast discrimination. This has led to the suggestion that the visual periphery is inherently insensitive to positional relationships due either to its limited sampling capability (Levi & Klein, 1985; Snyder, 1982) or to a deficit in neural processing (Hess & Watt, 1990; Virsu, Näsänen & Osmoviita, 1987). For the purpose of representing images with coherent spatial structure, the phase of the spectral components making up the image is generally more important than their magnitude (Burton & Moorhead, 1981; Oppenheim & Lim, 1981). Moreover, spectral textures whose component phases differ can vary in appearance from spatially coherent to random (Porat & Zeevi, 1989). In order to determine whether variations in component phase affect the perception of position information in complex textures, comparisons must be made between a given *coherent* texture and a reduced version of it in which the phase information is appropriately decreased (cf. Harvey, Rentschler & Weiss, 1985; Hübner, Caelli & Rentschler, 1988).

In the present study, we first determined the minimum number of localized sinusoidal components necessary to produce a texture that is preattentively equivalent to a standard texture whose phases were distributed randomly. The number of components in the standard represented a compromise between the sensitivity of the human visual system to the two-dimensional frequency components making up the textures and the requirement that the textures reflect at least some of the complexities inherent in natural images (Field, 1987; Porat & Zeevi, 1989). We next determined whether an appropriate magnification of these textures would result in perceptually equivalent stimuli in foveal and peripheral vision, as has been found to be the case for simple luminance and contrast stimuli. Finally, we varied the phase information in a series of textures by changing the bandwidth over which the component phases were distributed. This was done in order to determine if the changes in structural coherence, associated with increases in phase-bandwidth, are inherently different from the spatial alterations associated with changes in the spatial frequency and orientation of the components. For all of the stimuli tested, our major concern is with the perceptual similarity of textures consisting of different amounts of information. Although it may not at present be possible to establish how perceptual similarity ratings are related to the overall pattern of activity in a presumed set of early visual mechanisms, it may be useful to determine whether they change in a predictable way with known changes in mechanism properties such as occur, for instance, across the visual field.

METHODS

Observers

Three observers, two females and one male, participated in the present series of experiments. Observers LK and SP were in their mid-twenties, were unaware of the purpose of the study, and were compensated for their participation. Observer GG was 38 yr old and was one of the authors. All observers had normal uncorrected vision.

Apparatus

Stimulus generation, data collection, and data analysis were under the control of an IBM PC and a PCVision video board (Imaging Technology Inc.). Stimuli were presented on Conrac monitors (Model 7241C19) using only the green channel (P22 phosphor). For the central (0.75°) condition, the two textures (see below) making up each stimulus were presented, side by side, on the same monitor and were viewed at a distance of 3 m after reflection by two front-surface mirrors. The stimuli were presented in a $3.8° \times 7.6°$ portion of the monitor display, which was maintained at the mean luminance of 48 cd/m^2 during the interstimulus interval. The fixation point was a small black dot which was placed directly on the monitor screen. For the peripheral (20° on the horizontal meridian) condition, the same pairs of textures (suitably scaled, see below) were presented on two separate monitors that were viewed directly from a distance of 1.5 m. A large cardboard screen was used to provide a homogeneous surface between and around the monitors. Two holes were cut in the screen such that only the left texture of the stimulus pair on the left monitor and the right texture of the stimulus pair on the right monitor were visible. The resulting visual impression was that the two halves of the monitor display used in the central condition had been separated along the horizontal meridian. A green LED mounted in the screen midway between the two monitors served as a fixation point.

The stimulus display monitors were calibrated using a Spectra Spotmeter photometer (Photo Research). The function relating image pixel value to monitor luminance was linearized using a look-up table constructed in accordance with the measured response characteristics of the monitors. A mean luminance display was on continuously, and the experimental room was otherwise dark. The observers were provided with a chin and head rest and were asked to enter their rating response on a computer keyboard.

Stimuli

The present study required complex stimuli that approximated real-world imagery and whose spatial frequency and orientation content could be accurately specified. A compromise was reached between these requirements by using stimuli composed of multiple, localized, spectral components. Stimuli of this kind have been used to approximate both natural images (Porat & Zeevi, 1989) and other images with continuous power spectra (Kronauer *et al.*, 1982). Each of the spectral components used here (see below) was completely specified by its two-dimensional spatial frequency (i.e. spatial frequency and orientation) and its phase.

The perceived structure of complex textures is dependent on both local and global features that represent interactions among components at different scales (cf. Badcock, 1984), and hence may not be invariant with image magnification. The approach to stimulus magnification adopted here was to construct textures using two-dimensional spatial frequencies that would be clearly visible for the stimulus sizes and eccentricities studied. We used threshold contrast data as our criterion rather than suprathreshold data because the former are more conservative as to the range of spatial frequencies presumed visible at a given contrast level and at a given eccentricity. Based on typical contrast sensitivity data (cf. Johnston, 1987; Banks, Sekuler & Anderson, 1991) a spatial frequency range of 1–12 c/deg with logarithmic steps was chosen. All spatial frequencies in this range were within 0.5 log units of the peak contrast sensitivity.

It was also necessary to decide how many components would be tested. Textures containing between 2 and 96 components were generated in order to identify an appropriate range. Textures composed of more than about 80 components appeared qualitatively different from the others in the series in that they appeared to be of higher frequency than would be expected from the frequency of their components. Therefore, we chose to limit our textures to 64 components. The minimum number of components was chosen so that textures did not appear to be composed of individual gratings. The lower limit based on this criterion was about 8–10 components, and so 12 components was chosen as the minimum number for the present study.

For both the orientation-components and phase-bandwidth stimulus sets, two-dimensional textures were generated off-line by adding together between 12 and 64 Gabor functions each with a luminance distribution, $L(x,y)$ of the form:

$$L(x,y) = L_0(x,y) + \exp\left\{-\pi\left[\left(\frac{x}{D}\right)^2 + \left(\frac{y}{D}\right)^2\right]\right\} \cdot \cos(2\pi f_x x + \phi_x + 2\pi f_y y + \phi_Y), \quad (1)$$

where $L_0(x,y)$ is the mean luminance, D is the width of the gaussian window at the point where the gaussian has fallen to 0.46 of its peak value, f_x and f_y are the spatial frequency projections in the horizontal and vertical directions respectively, and ϕ and ϕ_y are the associated phase shifts. The spatial frequencies referred to in this report correspond to $\sqrt{f_x^2 + f_y^2}$.

As noted above, the component spatial frequencies for each texture were distributed logarithmically between 1 and 12 c/deg. This was accomplished by first generating a series of numbers, A_i, from 0 to 1, according to the formula, $A_i = (i-1)/(N-1)$, where N is the number of spatial frequency components, and i is an integer between 1 and N. The spatial frequencies for the set were then determined by raising 12 to the power of each A_i. Various numbers (M) of orientations were associated with each of the spatial frequencies. Specifically, the orientations were linearly spaced between 0° and $180-(180/M)°$.

For the stimuli used to investigate the effects of number of component orientations (Fig. 1), each of the Gabor components making up a particular texture had the same effective width but no two textures had both the same number of spatial frequencies (#SFs) and the same number of orientations (#ORs). Each component also had a unique phase. The level of phase quantization among components depended on the number of components (n) in the texture. For an n-component texture, the levels of phase quantization corresponded to the values of $2\pi m/n$ radians where m is an integer between 1 and n. In order to minimize the effects of local luminance variations (cf. Badcock, 1984) on the similarity judgments, four different phase stimuli were generated for each #SFs–#ORs combination. The four stimuli were generated by randomly reassigning each of the phases, obtained as described above, to the various components of the original stimulus.

For the stimuli used to investigate the effects of phase-bandwidth, textures were generated by adding together either 24 or 64 Gabor components. Four groups

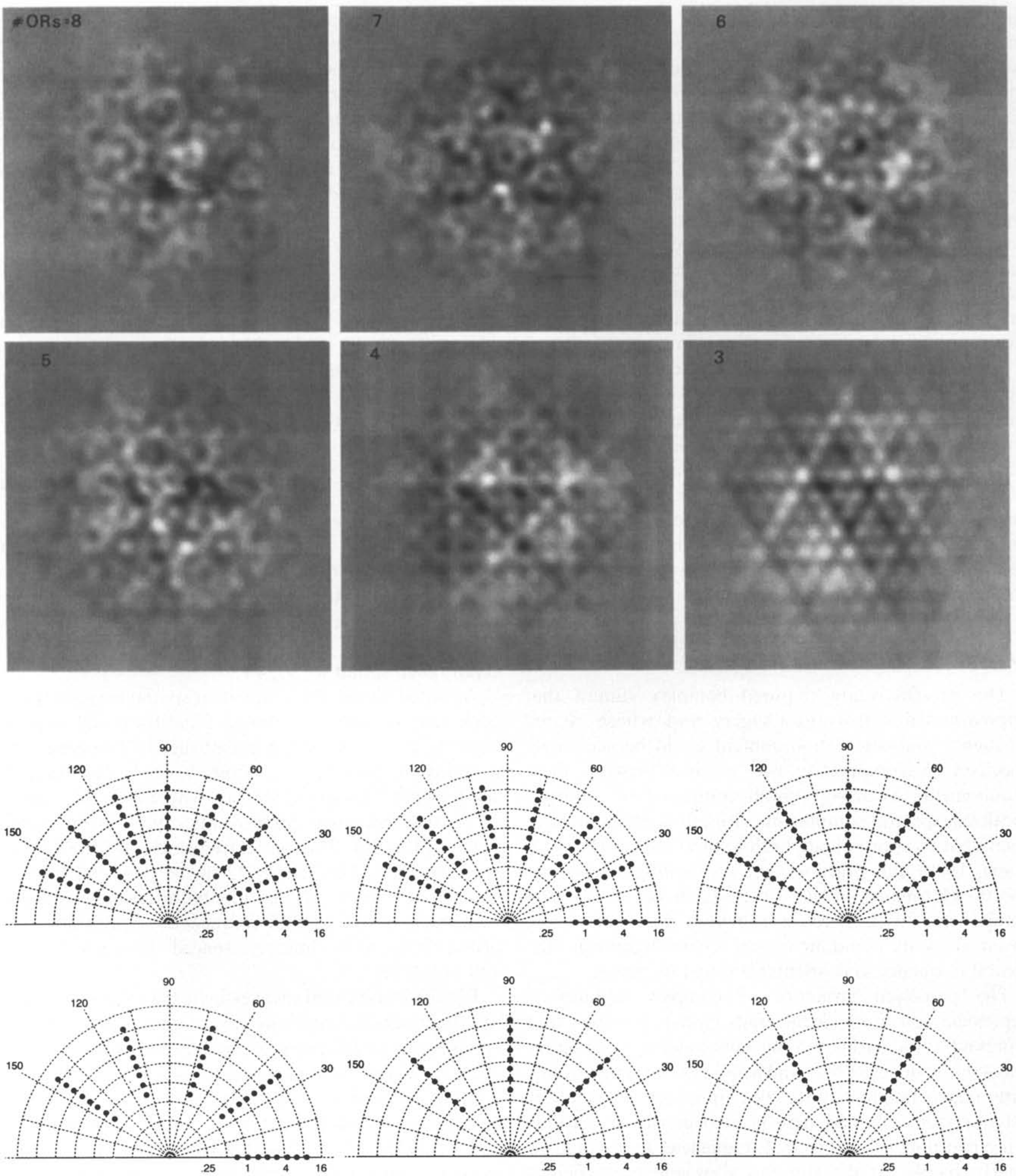

FIGURE 1. A typical texture set used in the orientation portion of the present study. The textures in this set are composed of 8 spatial frequencies at each of 8, 7, 6, 5, 4 or 3 orientations. The component distribution for each stimulus is shown in the lower portion of the figure. The component phases for all textures were randomized. The texture at the upper right (8SFs/8ORs) is one of the textures that was used as a standard stimulus on each trial. The other three standard stimuli were obtained by randomly redistributing the component phases of the 8SF/8OR texture.

of textures were produced, using the following combinations of #SFs and #ORs, respectively: 4 and 16; 4 and 6; 8 and 8; 8 and 3. Once again, the phase of each Gabor component relative to the center of the texture was randomly selected (see below). For a given random texture, any different randomization of the component phases would not be expected to significantly alter the appearance of the texture, especially under preattentive viewing conditions. Further, the visual periphery is particularly insensitive to alterations in the relative phase of the components of a random texture. On the other hand, for a coherent texture, while any randomized phase version of the original would be expected to appear much different than the original, all of these versions would

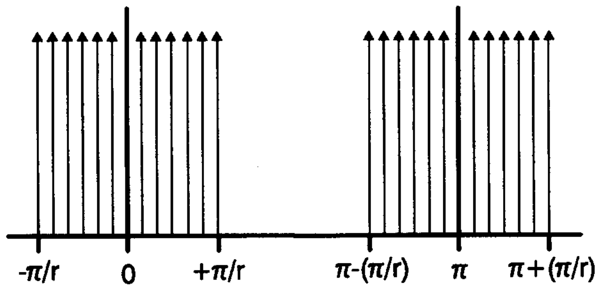

FIGURE 2. The distribution in phase space of the components of a hypothetical 24-component texture. One-half of the components were distributed around zero phase and one-half about π phase in order to avoid loss of texture structure due to the luminance saturation that occurred near the center of the image where the gaussian envelope peaked for all components. The parameter r determines the phase-bandwidth and is inversely proportional to it.

appear similar to each other and hence would appear equally different from the original. Therefore, the disruption of the perceived coherency (or structure) of multicomponent texture stimuli was studied by varying their phase-bandwidth, defined as the width of the region (in phase space) over which the phases of the component Gabor functions were distributed. Shown in Fig. 2 is the phase distribution of a hypothetical 24-component stimulus set. In order to avoid extensive areas of luminance saturation, especially near the center of the resultant image, one-half of the components was distributed about phase $= 0$ rad and the other half about phase $= \pi$ rad. The phase-bandwidths tested were determined by the parameter r (see Fig. 2), which was set equal to 0 (i.e. all components at the same phase), 13/3, 13/4, 13/5, and 13/6. An example of a phase-bandwidth stimulus set (corresponding to 8SFs/8ORs) is shown in Fig. 3. The bandwidths corresponding to this and all other sets used in the present study correspond to $2\pi/r$ and hence equal 0, $6\pi/13$, $8\pi/13$, $10\pi/13$, and $12\pi/13$ rad.

The stimuli presented at 0.75° eccentricity were 0.75° in diameter (at 0.46 of the peak luminance) and the stimuli presented at 20° eccentricity were either 1.5° or 3.0° in diameter (i.e. corresponding to magnification factors of 2 and 4). A magnification factor of 4 was the largest we could test given the size of our display monitor and our decision to minimize observer accommodation by maintaining a viewing distance of at least 1.5 m.

When modulating a sinusoidal luminance distribution by a gaussian, a shift in the mean luminance results whenever the sinusoid is not antisymmetrical about the center of the gaussian (i.e. for all sinusoids except a sine wave with phase equal to an integer multiple of π rad). Since the textured patterns extended over only a portion of the display, there would be a mismatch in the mean luminances of the textures and the background if image contrast were maximized using the most straightforward luminance scaling procedure of assigning the minimum (maximum) display luminance value to the minimum (maximum) pixel value. Therefore, to assure that the mean luminance of the pattern would match that of the background, the luminance range of each multicomponent texture was scaled as follows. Either the maximum pixel value in the texture was set equal to the maximum luminance (i.e. twice the mean luminance), or the minimum value was set equal to the minimum luminance, depending on whether the minimum (most negative) or maximum (most positive) pixel value was farther from zero. The gaussian envelope was limited to $\pm 1.25D$ [see equation (1)] with all pixels beyond this limit set equal to the mean luminance.

Procedure

The observer first adapted for about 5 min to the ambient illumination in the experimental room. The final minute of adaptation was spent viewing a homogeneous field corresponding to the mean luminance of the stimulus textures to be presented. The observer initiated the session using the keyboard, and the first texture pair was presented for 167 msec. The observer then rated the similarity of the members of the pair by pressing the appropriate numeric key on the keyboard. The next pair was presented 2 sec after the observer's response, and this cycle continued for the remainder of the session. In the component-orientation portion of the study, eighteen combinations of #SFs and #ORs were tested in each session. Each of the four phase-versions corresponding to each #SF–#OR category was paired with each of the four phase-versions in the #SFs = 8/#ORs = 8 category—the latter thus serving as standard stimuli. Each of the resulting pairs was presented eight times (four with one of the standards on the right and four with it on the left) in each experimental session, resulting in a total of $18 \times 4 \times 8 = 576$ trials randomized with respect to all variables mentioned above. The three combinations of eccentricity and test stimulus diameter (referred to here as the eccentricity-size factor) were tested in a different order for each observer. The testing procedures were similar in the phase-bandwidth portion of the study, except that there was a single standard stimulus corresponding to each of the four stimulus sets described earlier. The phase-bandwidth of the standard stimuli was zero indicating that half of the components had a phase of zero and half had a phase of π rad.

For both the component-orientations and phase-bandwidth portions of the study, the observers were asked to rate, on a scale from 1 (most dissimilar) to 7 (most similar), the perceived similarity of the two textures making up each stimulus. At least two practice sessions were run to acquaint the observers with the full range of possible differences between the pairs of textures. As noted above, in the component-orientation portion of the study there were four phase versions of each of the standard and test stimuli. Similarity ratings were therefore obtained between each phase version of each stimulus and each phase version of the standard (i.e. the stimulus for which #SFs = 8 and #ORs = 8). Thus, a high similarity rating does not necessarily mean perceptual equivalence since the baseline for each rating is the perceived difference, not among physically identical

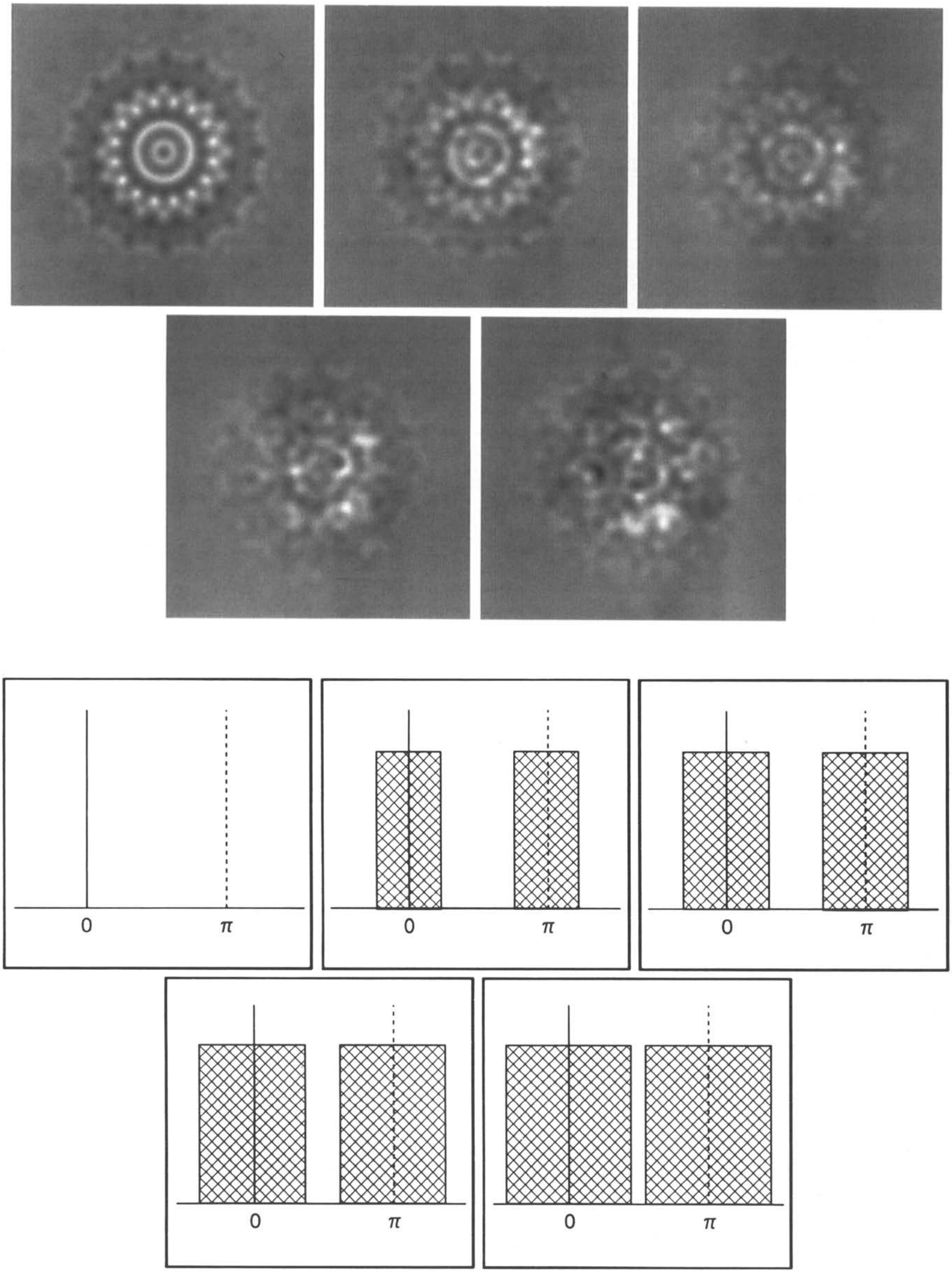

FIGURE 3. A typical texture set used in the phase-bandwidth portion of the present study. Each of the textures shown is composed of 64 components (8SFs and 8ORs) evenly distributed in the phase space shown in the graphs in the lower portion of the figure. A wider distribution in phase space is associated with a greater spatial disruption of the original texture pattern, which is shown at the upper left.

stimuli, but rather among stimuli that differed in the distribution of phase among each of their components.

Data analysis

For the component-orientations portion of the study, data from the 0.75°/0.75° condition were compared with data from each of the other two conditions (20°/1.5° and 20°/3.0°) in two separate ANOVAs. Each of the ANOVAs included three factors (eccentricity size, #SFs, and #ORs), and were performed using a randomized block design with observers as the block. Only some levels of the #ORs factor were included (i.e. those that were assessed at more than one level of the #SFs factor.) Even so, there were a small number of missing cells because these two factors were not completely crossed. All observer interactions were pooled into a single error term that was used to test the significance of all main effects and interactions.

For the phase-bandwidth portion of the study, data from the 0.75°/0.75° condition were again compared with data from each of the other two conditions (20°/1.5° and 20°/3.0°) in separate ANOVAs. Each of these ANOVAs included four, completely crossed factors (phase-bandwidth, eccentricity size, number of components, and observer). Each of the data sets analyzed in the two ANOVAs described above were further analyzed by four additional ANOVAs, one for each of the two levels of the number-of-components factor for each of the two observers.

RESULTS

Since our initial concern was the relationship between rated similarity and number of components, an analysis was first performed on these two variables. An example of these data from one observer and one eccentricity-size condition are shown in Fig. 4. The data show that the

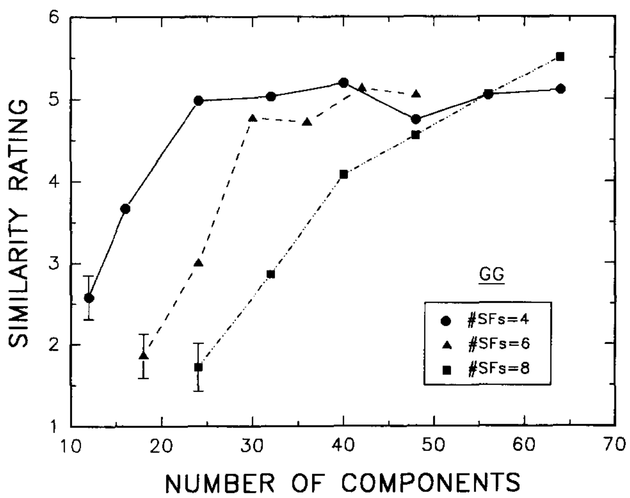

FIGURE 4. Similarity ratings as a function of the number of components in three sets of textures composed of either 8, 6, or 4 spatial frequencies. The data for all numbers of spatial frequencies have a similar form suggesting that they might be accounted for by a single function if similarity rating were plotted against number of orientations (see Fig. 5). The error bars represent mean 95% confidence limits for the data points of each curve.

general shape of the rating functions is the same for each number of spatial frequencies (#SFs), and that there appears to be a systematic shift along the horizontal axis as a function of the #SFs in the stimulus texture. This suggested that number of orientations was the appropriate variable on which to perform subsequent analyses.

Number of orientations

Shown in Fig. 5 are mean similarity ratings, plotted as a function of the number of orientations (#ORs) in the test stimulus, for all three observers and all three eccentricity-size conditions. The three sets of points within each of the nine panels were obtained using test stimuli containing either 4, 6, or 8 spatial frequencies. As can be seen from the figure, there is considerable overlap among the three sets of points, indicating that the #SFs, and hence the total number of components, in the texture stimulus has relatively little effect on perceived similarity. This observation is supported by a nonsignificant #SFs main effect and a nonsignificant #SFs × #ORs interaction in each of the two ANOVAs.

As is evident from the data of Fig. 5, rated similarity initially increases as the #ORs in the test stimuli is increased, and then remains approximately constant as the #ORs approaches (and exceeds) the #ORs (i.e. 8) in the standard stimuli. This observation is reflected in the significant #ORs main effect in both the ANOVA comparing the 0.75°/0.75° and 20°/1.5° conditions ($F_{6,67} = 142$, $P < 10^{-4}$) and the ANOVA comparing the 0.75°/0.75° and 20°/3.0° conditions ($F_{6,69} = 138$, $P < 10^{-4}$). In order to estimate the critical #ORs (i.e. the #ORs at which rated similarity no longer changes as the #ORs is increased), we have fitted two straight lines to the data in each panel of Fig. 5 using a least-squares criterion. A horizontal line was fitted to the rating data obtained for 8 and 10 orientations, and a second straight line was fitted to the rating data obtained for 3, 4, and 5 orientations. The intersection of the two regression lines in each panel was used to estimate the critical #ORs—i.e. the #ORs above which the test textures were perceived to be as similar to the standard textures as the various phase versions of the standard textures were to each other. Estimates of the critical #ORs are indicated by the arrows placed along the horizontal axis in each of the panels of Fig. 5.

For all observers, the #ORs at asymptote is approximately the same for the 0.75°/0.75° and 20°/1.5° conditions, which is consistent with the fact that the eccentricity size × #ORs interaction did not even approach significance in the ANOVA comparing these two conditions ($F_{6,67} = 0.26$, $P = 0.95$). Further, there was no main effect of eccentricity size. Thus, doubling the size of the peripheral texture stimuli was sufficient to produce ratings similar to those obtained for the smaller stimuli near the fovea. In contrast, the #ORs at asymptote for the 20°/3.0° condition is greater than for the 0.75°/0.75° condition, and this is reflected in the significant eccentricity-size × #ORs interaction in the ANOVA comparing these conditions ($F_{6,69} = 4.72$, $P < 0.0004$).

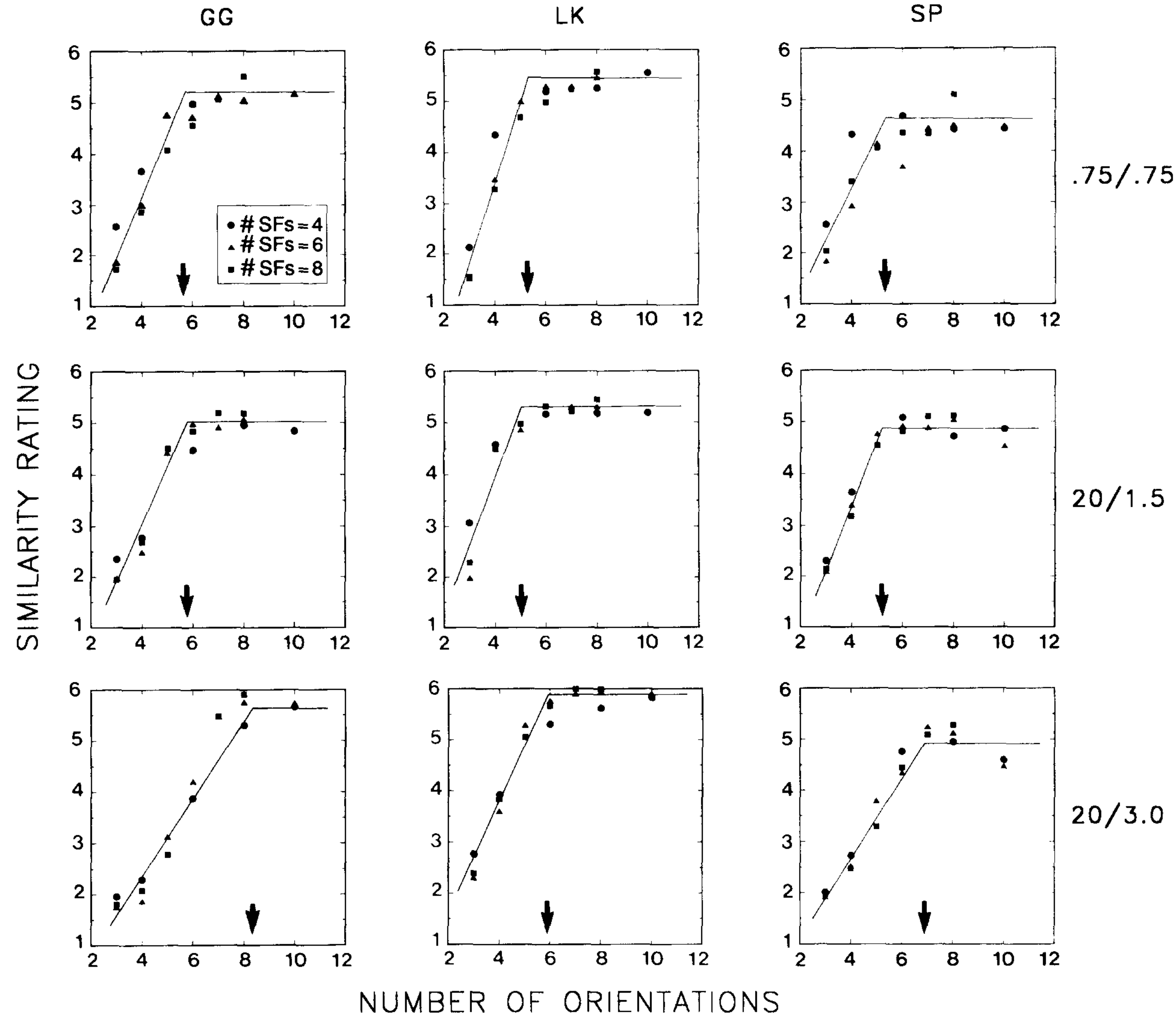

FIGURE 5. Similarity ratings for each of the three observers as a function of the number of orientations (#ORs) making up the stimulus textures. Each panel shows a data set replotted from one similar to that of Fig. 4. The top panel for each observer shows data obtained for a texture pair (i.e. a 0.75° standard and a 0.75° test) presented at 0.75° on either side of the fixation point. The middle panels show the data obtained for textures composed of the same components but doubled in size to 1.5° (i.e. a magnification factor of 2) and presented at 20° eccentricity. The bottom panels show the data obtained using 3.0° textures (i.e. a magnification factor of 4) again presented at 20°.

Phase-bandwidth

Mean similarity ratings as a function of phase-bandwidth, obtained from observers GG and LK, are shown in Fig. 6(a,b) respectively. The four panels in each figure correspond to the four combinations of #SFs/#ORs tested. For the two ANOVAs (one comparing the foveal condition with each of the peripheral conditions), all main effects and interactions were significant ($P < 10^{-4}$) except for the observer × bandwidth and number-of-components × eccentricity-size interactions. Both ANOVAs indicated a significant decrease in rated similarity as phase-bandwidth was increased ($F_{4,7634} = 1087$, $P < 10^{-4}$; $F_{4,7000} = 893$, $P < 10^{-4}$). The decrease was greater for the foveal condition than for either of the peripheral conditions, as indicated by significant bandwidth × eccentricity-size interactions ($F_{4,7634} = 74.2$, $P < 10^{-4}$; $F_{4,7000} = 115$, $P < 10^{-4}$). The significant bandwidth × eccentricity-size × number-of-components interactions ($F_{4,7634} = 25.2$, $P < 10^{-4}$; $F_{4,7000} = 3.49$, $P < 0.008$) further indicate that the difference between the bandwidth effects in the foveal and peripheral conditions varied with number of components. Of the four additional ANOVAs, performed in order to determine which level (24 or 64) of the number-of-components factor resulted in the larger bandwidth × eccentricity-size interaction, the relevant F-ratios of three (all except number of components = 24 for observer GG) showed that the interaction was larger for the smaller number of components.

DISCUSSION

Given a texture composed of a large number of oriented, spatial frequency components, can a perceptually equivalent texture be produced from a smaller number of such components? The present data indicate

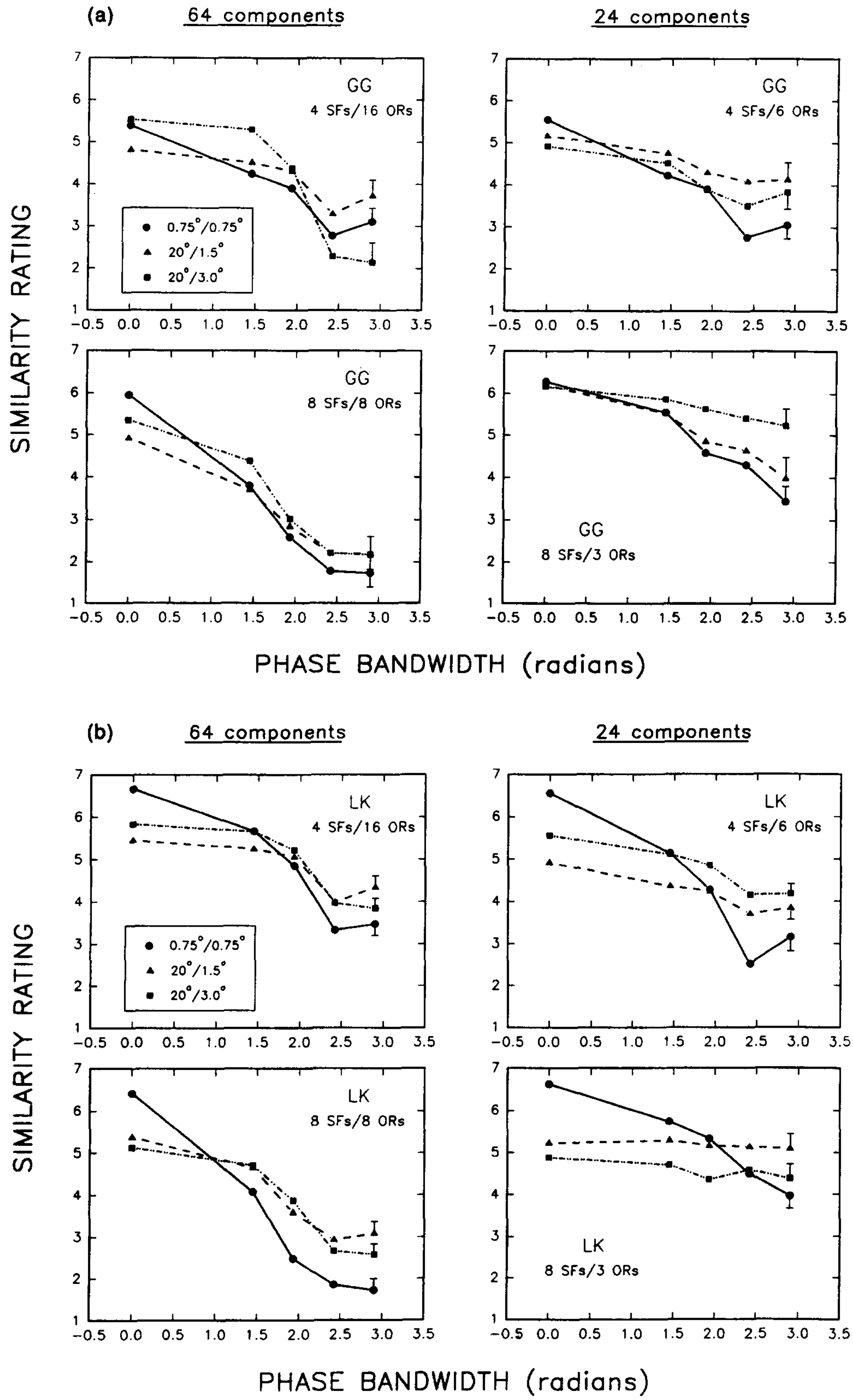

FIGURE 6. Similarity ratings as a function of phase-bandwidth (see Fig. 2) for 0.75° stimuli presented at 0.75° eccentricity (●) and for either 1.5° or 3.0° stimuli (representing magnification factors of 2 and 4 respectively) presented at 20° eccentricity. (a) The data for observer GG obtained using either 64 (left panels) or 24 total components and an orientation density (#ORs/#components) of either one-quarter (upper panels) or one-eighth. Analogous data for observer LK are shown in (b).

that complex, suprathreshold textures can be generated which are *preattentively* indistinguishable from textures containing many more components, provided that the former contain at least 5–7 different orientational components. As was noted by Kronauer *et al.* (1982), however, there are certain conditions which must be met in order to establish classes of perceptually equivalent stimuli. For instance, Kronauer *et al.* found that a relatively few spectral components could adequately simulate continuous bandlimited noise if the spatial frequency and orientation of the components was restricted to the dimensions of a visual channel. Although the distribution of components was not explicitly studied here, the present data indicate that a class of equivalent stimuli can be produced using spectral components that are uniformly distributed over the range of possible orientations.

Salience of component orientation

The data of Fig. 4 show, as might be expected, that rated similarity increases as the number of components making up the test texture approaches the number of components in the standard texture. More surprising perhaps is that the rate of increase in perceived similarity is largely independent of the number of spatial frequencies (#SFs) in the texture series. This is true despite the fact that the three texture series, which produced the individual functions of Fig. 4, are easily distinguishable, and that all textures were rated relative to the same (phase) set of standard textures consisting of eight orientations and eight spatial frequencies. The similarities in the form of the functions of Fig. 4 become more obvious when rated similarity is plotted as a function of the number of orientations (#ORs) in the test texture. Data plotted in this form are shown in the upper row of Fig. 5 for each of the three observers at a retinal eccentricity of 0.75°. Plotting the data in this way is justified by the ANOVA results described earlier, and clearly shows that the #ORs in the test texture is the primary determinant of perceived similarity.

The orientation of pattern elements is known to be an important determinant of both threshold and suprathreshold form perception. For instance, differences in the orientation of texture micropatterns can underlie both perceptual grouping (Beck, 1966) and preattentive texture segregation (Julesz, 1981; Beck, 1982; Nothdurft, 1985). The visual salience of pattern orientation is reflected also in the orientation columns in the visual cortex (Hubel & Wiesel, 1962; Carpenter & Blakemore, 1973). The orientation columns are, in turn, one manifestation of presumed visual channels (Hubel & Wiesel, 1968) that have a two-dimensional spatial (and spectral) structure with an inherent orientation. The data of Fig. 5 suggest, however, that orientation and spatial frequency may not be perceptually equivalent. Specifically, as noted above, the data of Fig. 5 indicate that component orientation is a particularly important determinant of texture appearance. The fact that ratings are lower for textures composed of fewer orientations but not for those composed of fewer spatial frequencies suggests that less perceptual salience is attached to spatial frequency. The critical #ORs estimated from the intersection of the functions fitted to the data in the upper row of Fig. 5, is between 5 and 7. This result is consistent with threshold data, which suggest that there are 5–8 orientation channels with bandwidths of 15–30 deg (Daugman, 1984; Phillips & Wilson, 1984; Dannemiller & Ver Hoeve, 1990). Thus, we conclude that, given a multicomponent texture, a stimulus which is preattentively equivalent to it can be generated from significantly fewer spectral components, provided that those components are distributed so as to stimulate the full range of putative orientation channels. Observations of this sort have also been discussed in the context of other suprathreshold texture discriminations (cf. Richards & Polit, 1974; Caelli, 1982).

Perceptual equivalence across the visual field

Orientation-components stimuli. The data in the third row of Fig. 5 were obtained at 20° eccentricity using stimuli that were 4 times larger in diameter than those used to obtain the data in the first row of that figure (corresponding to 0.75° eccentricity). Even this relatively small magnification* [as compared to that found for other orientation-related preattentive discriminations (cf. Geri & Lyon, 1991; Nothdurft, 1985; Paradiso & Carney, 1988; Scobey, 1982; Virsu *et al.*, 1987)] resulted in an overcorrection of the data, in that both rated similarity and the critical #ORs (indicated by the arrows in Fig. 5) were significantly higher at 20° eccentricity. The data in the second row of Fig. 5 were then obtained (also at 20° eccentricity) using a magnification factor of 2. These ratings are more comparable to those obtained at 0.75° eccentricity in that both the maximum rating and the derived critical #ORs are now very similar.

There is substantial evidence that the visual cortex is organized hierarchically with higher levels performing successively more complex visual analyses (cf. Van Essen & Maunsell, 1983). Complex, spatially separated, suprathreshold textures and a similarity rating task were

*It has been contended (cf. Johnston, 1987; Watson, 1987) that psychophysical eccentricity scaling factors should be obtained by measuring threshold to a series of progressively magnified versions of a stimulus centered at a given eccentricity. Although this technique may be appropriate when small scaling factors are estimated for certain stimuli (Levi, Klein & Yap, 1988; Whitaker, Mäkelä, Rovamo & Latham, 1992), it does not resolve the inherent confounding of stimulus extent and stimulus location. For instance, the largest of the stimuli used by Watson (1987), while nominally located at 3° eccentricity, actually extended from the fovea to more than 6° into the periphery. Further, the scaling technique is not readily applied to complex, full gray-scale textures such as those used in the present study, because perceptually relevant aspects of the stimulus may vary in an unpredictable way as magnification is changed. Therefore, our references in the text to relative stimulus magnification at different eccentricities refer only to our measurements using a single stimulus size near the fovea. As we have described in the Methods, this single stimulus size was not chosen arbitrarily. Further, the stimulus magnification referred to here is analogous to that estimated in other studies of orientation-related discriminations (Nothdurft, 1985; Scobey, 1982; Vandenbussche, Vogels & Orban, 1986; Virsu *et al.*, 1987).

used in the present study and thus the data of Fig. 5 probably reflect a relatively high level of visual processing (cf. Lamme, Van Dijk & Spekreijse, 1992). Gattass *et al.* (1985) have summarized neurophysiological estimates, which indicate that cortical magnification is generally lower for higher visual-cortical levels. They present evidence that there are differences in the slopes of the functions that relate cortical magnification to eccentricity for various cortical areas. Although there is significant variability in their data, and there are inherent problems in obtaining estimates of the magnification factor near the fovea, it is clear that the highest cortical area tested (labeled MT) shows the greatest slope, and hence the greatest magnification factor. It is well known that extensive reciprocal connections exist among the various cortical areas, and it appears that visual information is progressively integrated at higher levels (cf. Van Essen & Maunsell, 1983). This integrative property of the visual cortex might be expected to reduce the perceptual magnification at higher levels because any of several stimulus properties (or combinations of those properties) may mediate the higher perceptual discrimination. Further, visual receptive field size increases with eccentricity at a greater rate for higher cortical areas (Gattass *et al.*, 1985). This latter observation is consistent both with the proposition that information is progressively integrated at higher cortical levels, and with the present finding that a 0.75°-diameter stimulus in the central visual field is preattentively equivalent to a 1.5°-diameter stimulus in the periphery.

Phase-bandwidth stimuli. Increasing the phase-bandwidth of two-dimensional, multicomponent Gabor textures results in a disruption of their spatial structure (see Fig. 3). As is evident from our analysis of the data of Fig. 6 (specifically, the significant bandwidth × eccentricity-size interactions), this disruption is more consistently discriminated at 0.75° than at 20° even when the more peripheral data are magnified by the same factor of 4 that overcorrected the component-orientation data of Fig. 5. Hofmann and Hallett (1993) note that for simple, regular patterns, orientation and phase are effectively local parameters since the changes they induce are easily identifiable with features defined by local differences in luminance. If such features are mediating discrimination, they should scale as luminance or contrast and hence be equatable in the center and periphery. However, in more complex textures such as those used in the present study, the size of the luminance features may be a limiting factor in discrimination. Changes in phase-bandwidth tend to result in local feature changes that are on a smaller scale than those associated with changing the number of oriented components in a texture. Since spatial features are known to be more difficult to discriminate in the periphery, the larger stimulus magnification required to equate the phase-bandwidth stimuli may simply be due to a relative undersampling of those textures in the peripheral visual field (cf. Hess & Pointer, 1987).

As noted above, the largest stimulus magnification we were able to test here is less than those predicted by studies of other positional tasks such as vernier acuity (Klein & Levi, 1987; Levi *et al.*, 1985) and phase discrimination (Bennett & Banks, 1991; Rentschler & Treutwein, 1985). Thus, we cannot rule out the possibility that data like those of Fig. 6 could be adequately corrected by magnification factors estimated in the studies of positional discrimination mentioned above. Although our magnification estimates are based on only one stimulus size (see earlier), they suggest a difference in the stimulus magnification required to equate our #OR and phase-bandwidth stimuli across the visual field (see Figs 5 and 6). The magnification required to equate the #OR stimuli is less than that required to equate the phase-bandwidth stimuli, presumably because the latter differ more explicitly in the positional relationships of their features. The present stimuli share some of the structural complexities of real-world images, and component phase is known to be an important determinant of visual form in such images (Burton & Moorhead, 1981; Oppenheim & Lim, 1981). Our data suggest, therefore, that form discrimination in real-world images, which extend significantly into the periphery, may require more magnification than that suggested by simple luminance and contrast discrimination data.

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