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Narrow-Band 1, 2, 3, 4, 8, 16, 24, 32, 48, 64, and 96 Cycles/360º Angular Frequency Filters

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We measured human frequency response functions for eleven angular frequency filters using a forced-choice procedure in a supra-threshold summation paradigm. Each of the eleven functions of 17 experimental conditions was measured 4-9 times among 12 observers. Results show that, for the arbitrarily selected filter phases, maximum summation effect occurred at test frequency for all filters. These results lead to the conclusion that there are narrow-band angular frequency filters operating in human visual system mostly through summation surrounded by inhibition at the specific test frequency ranges. Our previous suggestion (Simas & Santos, 2002), arguing that summation for the higher angular frequency filters should occur if background angular frequency contrast were set to a maximum of 5 times the test frequency threshold, was supported.
Keywords: spatial frequency, angular frequency, narrow-band frequency filters, polar gratings, windmill stimuli

Se midieron, en observadores humanos, las funciones de once filtros sintonizados a la frecuencia angular. Para ello se empleó un procedimiento de elección forzada en un paradigma de sumación supra-umbral. Cada una de las once funciones de las 17 condiciones experimentales se midió 4-9 veces para 12 observadores. Los resultados mostraron que, para todos los filtros y para las fases de filtro elegidas arbitrariamente, el efecto de sumación máxima ocurría a la frecuencia de prueba Este tipo de resultado lleva a concluir la existencia de filtros de frecuencia angular de banda estrecha que operan en el sistema visual humano, mayormente a través de sumación rodeada por inhibición en los rangos específicos de la frecuencia de prueba. Por otra parte, se obtuvo apoyo para nuestra anterior sugerencia (Simas y Santos, 2002) respecto a que la sumación para los filtros de frecuencia angular más alta debe ocurrir si el contraste de frecuencia angular de fondo se fija en un máximo de 5 veces el umbral de la frecuencia de prueba.
Palabras clave: frecuencia espacial, frecuencia angular, filtros de frecuencia de banda estrecha, enrejados polares, estímulos de molino de viento

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Characterizing the human visual system through its psychophysical responses to the contrast of spatial frequency targets defined in Polar coordinates has been one of our main objectives. To this end, we have focused particularly on visual responses to the contrast of angular frequency stimuli.

Angular Frequency Stimuli

Angular frequency stimuli have appeared in the literature under a variety of names. Some studies have used terms like *radial targets, radial gratings, Polar gratings, windmill stimuli,* and *star-like,* among others (e.g., Gallant, Braun, & Van Essen, 1993; Gallant, Connor, Rakshit, Lewis, & Van Essen, 1996; Tootell et al., 1998; Wilkinson et al., 2000). Since 1985 (Simas, 1985; Simas & Dodwell, 1990), we have defined angular frequency as the number of cycles (modulated by a sine or cosine wave) within 360º, being adimensional, integer, and having spatial frequency independent from the distance of the observer.

Narrow-band Angular Frequency Filters

We first tried to demonstrate the existence of many narrow-band angular frequency filters in 1992 (Simas, Frutuoso, & Vieira, 1992). We used the arbitrary trigonometric definition of phase for background frequencies of 1, 2, 3, 4, 6, 9, 13, 16, 24, 32, 47, 64, and 96 cycles/360º. We measured seven filters at test angular frequencies of 2, 4, 9, 13, 16, 24, and 47 cycles. We used the same supra-threshold method of the present work. This method is based on that of sub-threshold summation (Kulikowski & King-Smith, 1973). Instead of using sub-threshold levels of contrast to measure the peak of the function, we used supra-threshold summation, where the test frequency is summated to a background frequency of higher contrast. While contrast of the test frequency is varied according to the observers' sensitivity, contrast of the background frequency is fixed above threshold (i.e., supra-threshold). Thus, if a stimulus containing only the background frequency is compared to a stimulus where the background frequency is summated to the test frequency, the only way to differentiate between the pair will be to detect the presence of the test frequency in one of them. Our results showed absolute or relative summation effects at the test frequencies employed, surrounded by strong inhibition. We concluded the existence of some selectivity for specific ranges of angular frequencies.

In a second study, we measured frequency response functions for seven angular frequency filters with maximum sensitivities centered on 1, 2, 3, 4, 8, 16 and 24 cycles/360º (Simas & Santos, 2002). This time, the background angular frequencies were 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 16, 24, 32, 48, 64, and 96 cycles/360º and the angular frequency stimulus phases were modified to present vertical and horizontal symmetry. Results showed maximum summation only for F_1, F_2, F_3, and F_4. Filters F_8, F_{16}, and F_{24} showed relative summation, but did not show strong selectivity at the test frequencies. As background stimulus contrast was set constant at 42%, we suggested that a new experiment should use a constant background stimulus contrast not higher than 5 times the respective test angular frequency detection threshold. We concluded that the lack of selectivity observed at angular frequencies 8, 16, and 24 cycles was probably due to the increased contrast sensitivity within this range as compared to the 1-4 cycles range.

Contrast Sensitivity to Angular Frequencies

Why work with angular frequencies when evidence from cells at the striate cortex point to orientation selectivity? Figure 1 shows contrast thresholds for angular frequencies as compared to that of sine-wave gratings. This result is a replicate of that one reported in 1997 (Simas, Santos, & Thiers, 1997). Using broadband gray stimuli, we found that the visual system is at least twice as sensitive to angular frequencies than to sine-wave gratings in their respective maximum sensitivity ranges. This would not necessarily be expected because some studies have shown inhibition among sine-wave gratings at orthogonal or other orientations (e.g., Tyler, 1975, 1978).

Physiological evidence that favor this type of stimuli configuration became available in the studies of Gallant and colleagues (Gallant, Braun, et al., 1996; Gallant, Connor, et al., 1993). Additional evidence came from studies of cells sensitive to expansion/contraction and rotation (Tanaka & Saito, 1989; Tanaka, Fukada, & Saito, 1989) and involved movement. More recently, Mahon and De Valois (2001) have used Cartesian and non-Cartesian stimuli and concluded that area V4 processing is not the result of areas V1 and V2 processing. Hegdé and Van Essen (2000, 2003) support that view based on the observation that area V2 of primates responds to various complex stimuli, including Polar gratings.

Indeed, if angular frequency is being used by any visual system, it requires integration over wide areas assembling information across hemispheres and quadrants. This implies integration across areas of the visual system, particularly for low angular frequencies. Furthermore, in our view, the processing of angular frequencies is coupled to that of radial frequencies modulated by Bessel spherical functions of order $n > 0$. This dependence is not valid if $n = 0$. In this case, we would be looking at global aspects of spatial processing like those investigated by Achtman and colleagues using Gabor patches (Achtman, Hess, & Wang, 2003).

The Present Study

In the experiments reported herein, we assume that higher areas of the visual system (e.g., V4 and IT) might be processing information in terms of coupled radial and angular

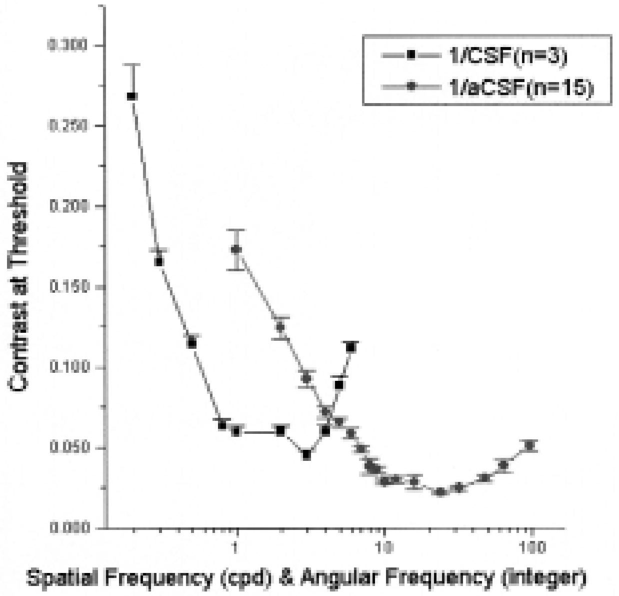

Figure 1. Contrast thresholds for angular frequencies (new phase definition) as compared to sine-wave gratings. This result is a replicate of that one reported in 1997 (Simas, Santos, & Thiers, 1997).

frequencies, as stated in Simas and Santos (2002). We partially replicated that study, and extended it further, by measuring angular frequency filters centered at 1, 2, 3, 4, 8, 16, 24, 32, 48, 64, and 96 cycles. We used the same supra-threshold method, phases and background angular frequencies with reduced constant contrast set to five times the respective test angular frequency contrast threshold. We expect to observe maximum summation effects at test angular frequencies due to this reduction in background contrast.

Method

Participants

Twelve (2 males, 10 females) 19-30 years old individuals with normal or corrected-to-normal vision participated of the measurements.

Equipment and Stimulus Material

All images were displayed on a 20” CRT monitor Sony BVM-1910 controlled by a 486 IBM-compatible microcomputer through a DT-2853 frame grabber. Experiments were run on-line. Measurements were made using pairs of stimuli composed of a single background angular frequency or of the sum of a background-angular-frequency-plus-test-angular-frequency. Background angular frequencies were either 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 12, 16, 24, 32, 48, 64, or 96 cycles/360º. The test angular frequencies were either 1, 2, 3, 4, 8, 16, 24, 32, 48, 64, and 96 cycles/360º. Figure 2 shows the eleven test angular frequencies used in the measurements. In the left column: 1, 2, 3, and 4 cycles/360º, center column: 8, 16, 24, and 32 cycles/360º and right column: 48, 64, and 96 cycles/360º. Please observe the selected phases.

Procedure

The supra-threshold summation procedure for each experimental condition involved a choice by the observer of which stimulus of a pair contained the sum background-angular-frequency-plus-test-angular-frequency. Only the contrast of the test angular frequency was increased or decreased according to a forced-choice method (Wetherill & Levitt, 1965). Contrast of the background angular frequency in both images of the pair was constant and set at five times its threshold, except for angular frequencies 1, 2, 3 and 4 cycles/360º where contrast was constant at 42%. The criterion for varying contrast of the test angular frequency was that of three correct choices to decrease contrast by a unit, and one incorrect choice to increase it by the same amount. All measurements were made binocularly at 150 cm distance, the mean luminance being 2.0 fL and the stimulus diameter being 7.2 degrees of visual angle. Maximum and minimum luminance were 2.2 and 1.8 fL, respectively.

The temporal sequence was initiated by a warning signal, immediately followed by a 2-s presentation of the first stimulus, followed by a 1-s inter-stimulus interval, followed by a 2-s presentation of the second stimulus and the observer’s response. The order of the stimulus in a pair was randomly selected. If the response was correct, it was followed by a beep and a 3-s inter-trial interval would start. The whole experimental session would vary in length depending on the errors and correct choices made by the observer, as a total of 10 pairs of peaks and valleys was necessary to end the session. Generally, it lasted about 15-25 min.

Each of the 17 experimental conditions required to measure each of the eleven filters was run at least two times on different days by at least two different observers. Thus, a total of 4-9 functions were measured for each filter, yielding a sample of 80-180 values to be averaged across observers for each of the 17 function point estimates. The distribution of the 12 participants among the filter measurements is indicated by the volunteers’ initials and the number of measured functions as follows: for F_1, 1 cycle filter, (NAS:3, MMM:3, MC:3); for F_2, 2 cycles, (NAS:3, ERB:3, TPL:3); for F_3, 3 cycles, (NAS:3, MC:3, MMM:3); for F_4, 4 cycles, (NAS:3, TPL:3, ERB:3); for F_8, 8 cycles, (DHE:3, GMM:2, LCO:2); for F_{16}, 16 cycles, (DHE:2, GMM:2, LCO:2); for F_{24}, 24 cycles, (LCO:2, GMM:1, RMT:1); for F_{32}, 32 cycles, (DHE:2, MSM:2); for F_{48}, 48 cycles, (DHE:2, DKO:2, MM:2); for F_{64}, 64 cycles, (DHE:2, RMT:2); and for F_{96}, 96 cycles. (DHE:2, RMT:2).

Figure 3 illustrates pairs of stimuli for filters at test angular frequencies of 1, 2, 3, 4, 8, 16, 24, 32, 48, 64, and 96 cycles/360º.

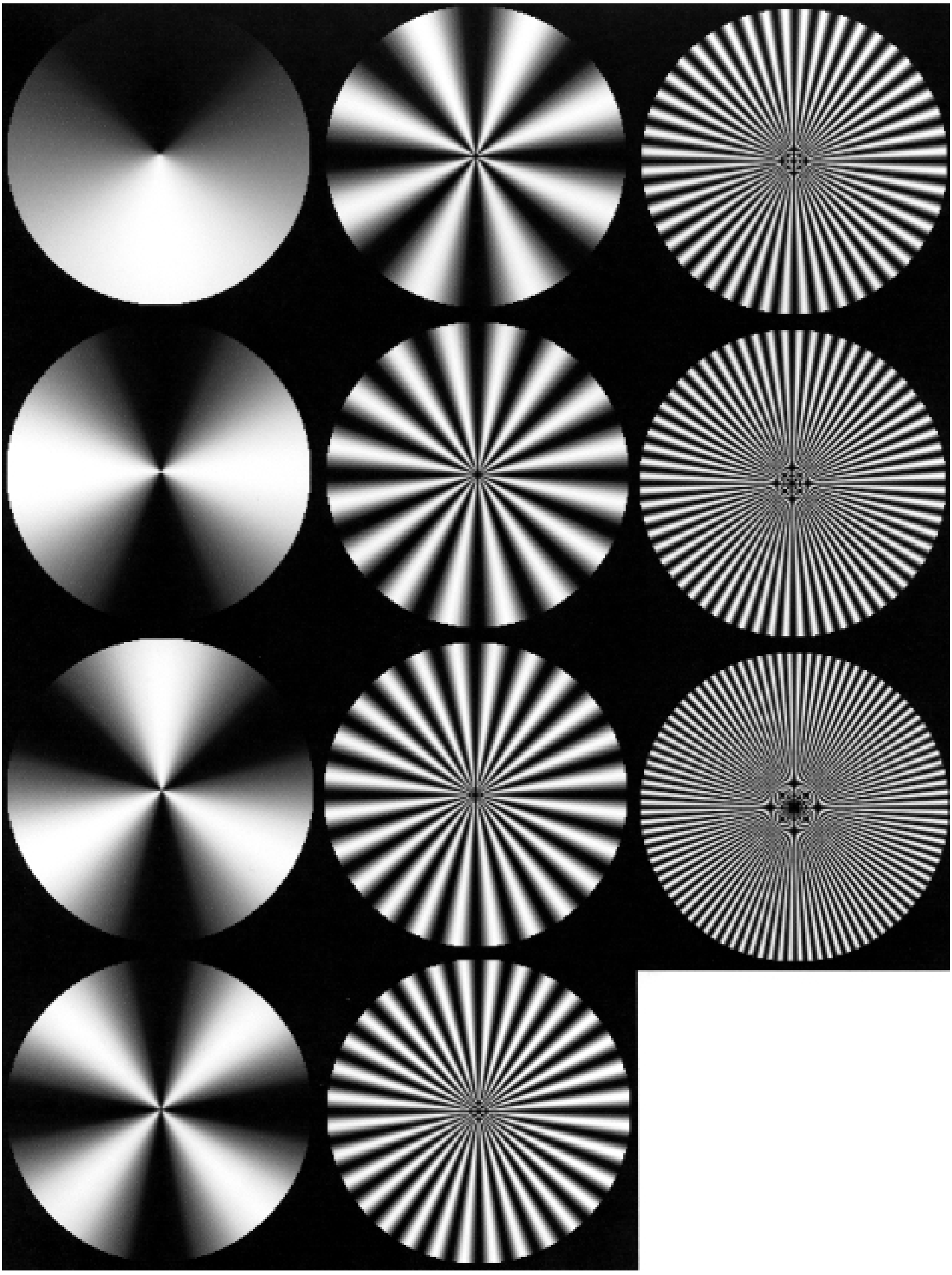

Figure 2. Phases used for eleven (1, 2, 3, 4, 8, 16, 24, 32, 48, 64, and 96 cycles) test angular frequencies in the experiment reported herein.

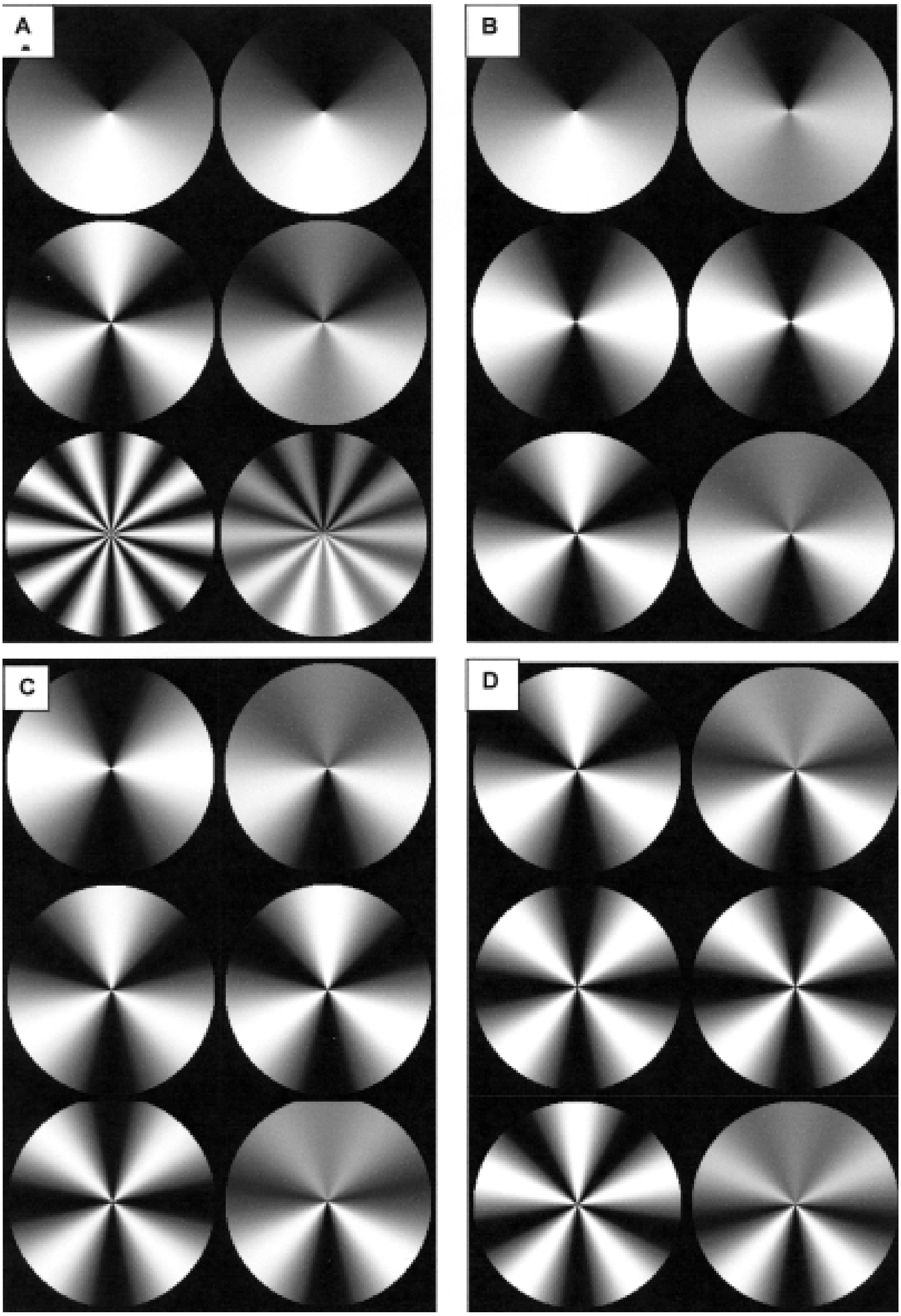

Figure 3. Pairs of stimuli for filters at test angular frequencies of 1, 2, 3, 4, 8, 16 and 24 cycles. (A) shows pairs 1 and 1+1 cycles (top), 3 and 3+1 cycles (center), and 10 and 10+1 cycles (bottom) for filter $F_1(q)$ centered at 1 cycle. (B) shows pairs 1 and 1+2 cycles (top), 2 and 2+2 cycles (center), and 3 and 3+2 cycles (bottom) for filter $F_2(q)$ centered at 2 cycles. (C) shows pairs 2 and 2+3 cycles (top), 3 and 3+3 cycles (center), and 4 and 4+3 cycles (bottom) for filter $F_3(q)$ centered at 3 cycles. (D) shows pairs 3 and 3+4 cycles (top), 4 and 4+4 cycles (center), and 5 and 5+4 cycles (bottom) for $F_4(q)$ centered at 4 cycles. (E) shows pairs 4 and 4+8 cycles (top), *(cont.)*

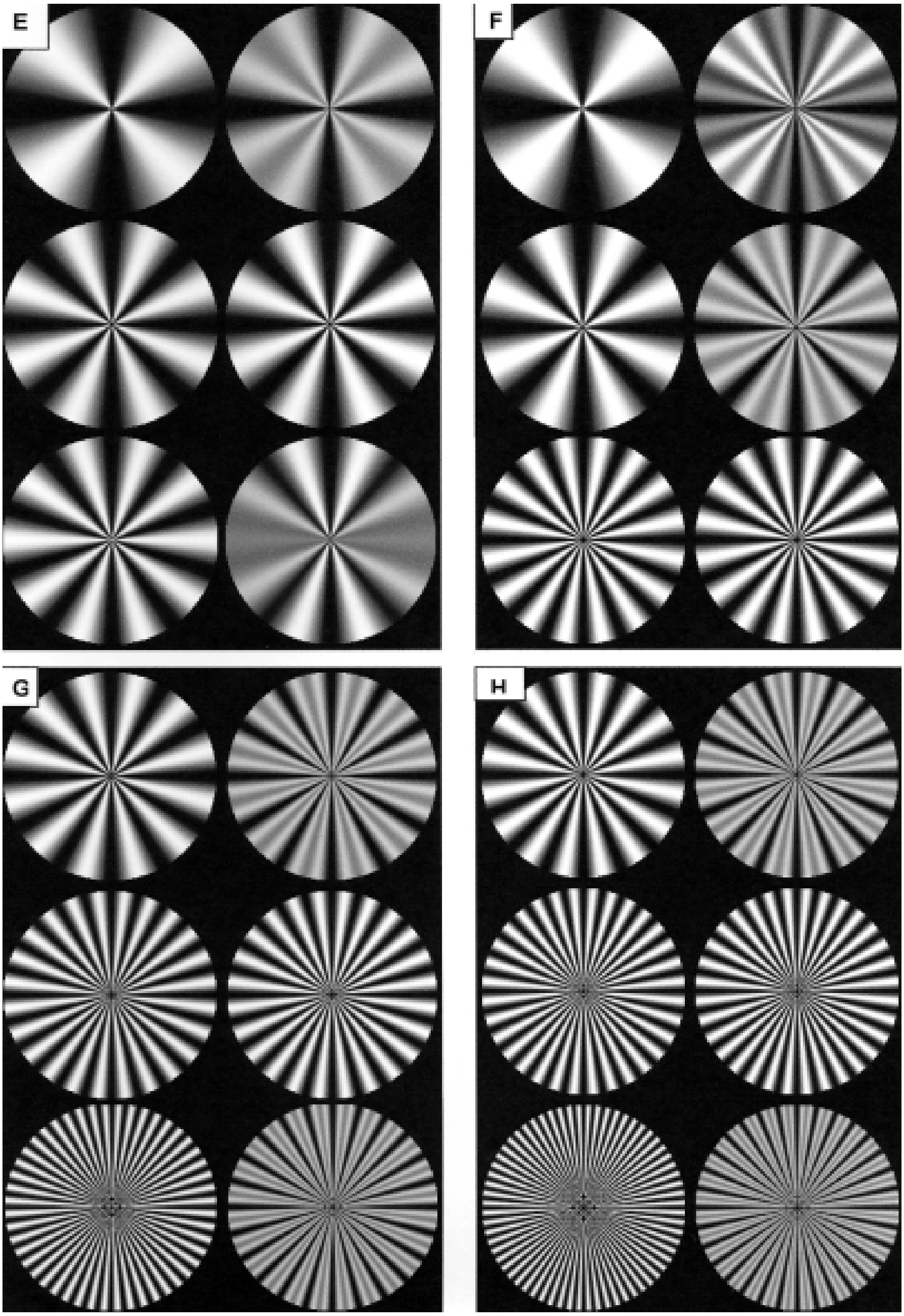

Figura 3 (cont.). 8 and 8+8 cycles (center), and 10 and 10+8 cycles (bottom) for $F_8(q)$ centered at 8 cycles. (F) shows pairs 4 and 4+16 cycles (top), 8 and 8+16 cycles (center), and 16 and 16+16 cycles (bottom) for $F_{16}(q)$ centered at 16 cycles and (G) shows pairs 12 and 12+24 cycles (top), 24 and 24+24 cycles (center), and 48 and 48+24 cycles (bottom) for filter $F_{24}(q)$ centered at 24 cycles. (H) shows pairs 16 and 16+32 cycles (top), 32 and 32+32 cycles (center), and 64 and 64+32 cycles (bottom) for filter F_{32} centered at 32 cycles.

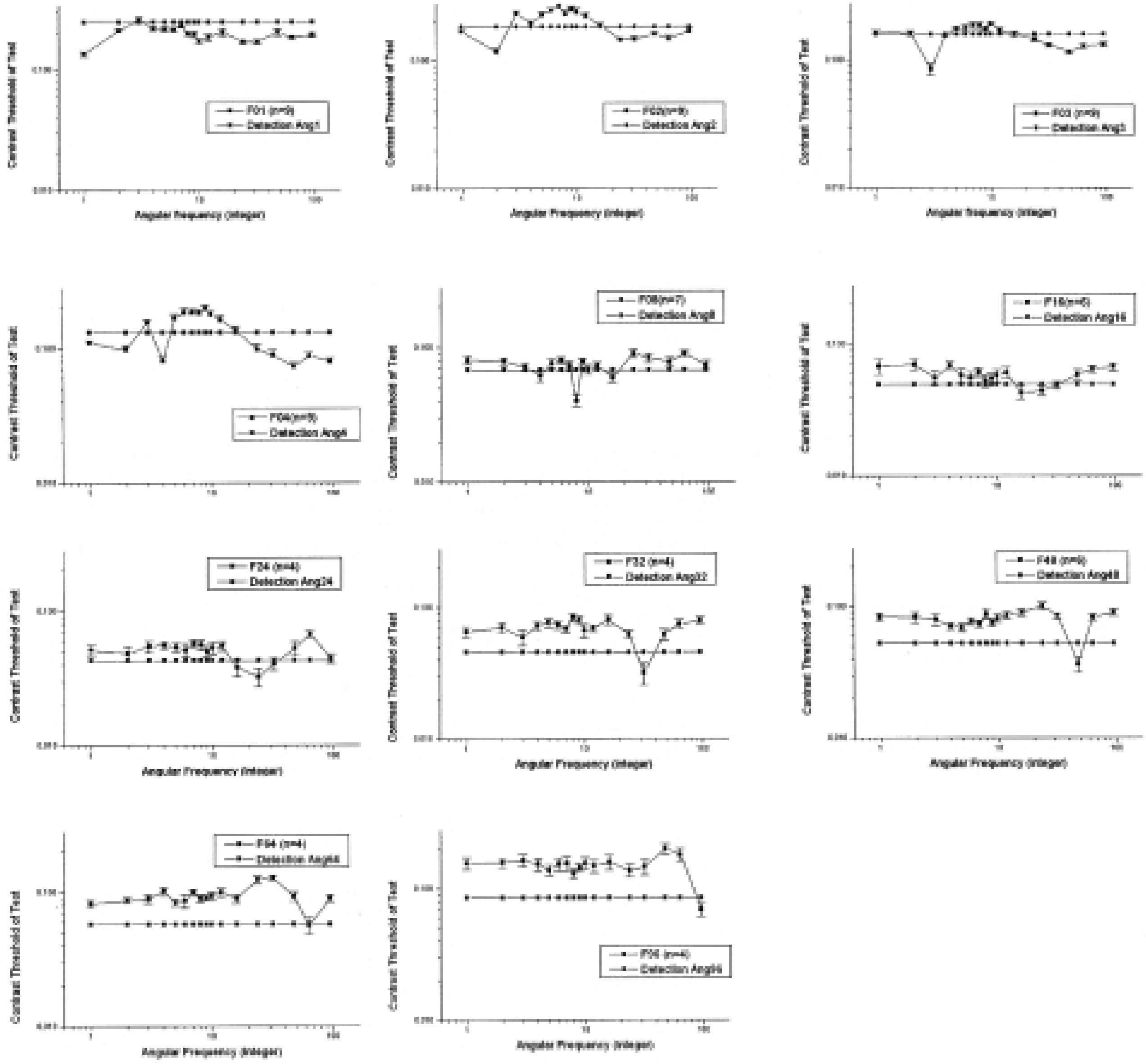

Figure 4. Frequency response functions for the seven measured filters F_1, F_2, F_3, F_4, F_8, F_{16}, F_{24}, F_{32}, F_{48}, F_{64}, and F_{96}. Angular frequency of the background stimulus is plotted as a function of the amount of contrast necessary to identify the presence of the test angular frequency in the summated pair. We are calling this threshold for the test angular frequency summated to each background frequency the *contrast threshold of test.* Legends at top right indicate the test frequency for each function. Horizontal lines indicate the respective detection contrast thresholds for each single test angular frequency stimuli.

Results

Figure 4 shows the frequency response functions for the eleven measured filters F_1, F_2, F_3, F_4, F_8, F_{16}, F_{24}, F_{32}, F_{48}, F_{64}, and F_{96}.

Our statistical treatment was to obtain the standard error of the mean for each distribution of 80-180 values measured for each of the 17-point estimates for a given narrow-band angular frequency filter and corrected for sample size using the *t*-Student statistic to obtain the 99% confidence level.

Maximum summation effects mostly surrounded by neighboring inhibition occurred at all test angular frequencies for the measured filters (see Figure 4). For the angular frequency filters F_1, F_2, F_3, and F_4, secondary summation also occurred far from their test angular frequencies at the high frequency end. This tendency was not observed for F_8 and all the remaining higher angular frequency filters.

Nine of the eleven angular frequency filters measured showed increased sensitivity by at least 50% (i.e., reduced contrast threshold) when the background angular frequency was identical to the test one. This was true when referring to the neighboring inhibitory bands. Filters F_1 and F_{16} showed increases of 48% and 35%, respectively. Thus, the ratio between maximum summation and maximum neighboring inhibition for all filters ranged from 1.49 to 2.59, clearly indicating filtering effects.

Therefore, the main observations throughout the results are the summation at the test angular frequencies and that the frequency of passage is generally surrounded on both sides by inhibition, sometimes, strong inhibition.

Discussion

The results clearly show filter selectivity for the test angular frequencies used. All filters again showed a main result observed in our work of 1992 (Simas et al., 1992) as well as the work of 2002 (Simas & Santos, 2002, in part), that is, the test frequencies showed summation surrounded on both sides by strong inhibition. This trend was found to be true for the eleven filters measured. Thus, as suggested in Simas and Santos, by setting the background angular frequency to a level of constant contrast equal to five times the detection threshold of the test frequencies of each filter (i.e., for filters F_8, F_{16}, F_{24}, F_{32}, F_{48}, F_{64}, and F_{96}), we were able to observe summation at the test angular frequency in all cases.

For filters F_1, F_2, F_3, and F_4, the background angular frequency contrast was set to 42% and the same summation effect was observed. Results on these four low angular frequency filters are also reported in Simas and Santos (2002).

Readers are reminded at this point that angular frequency stimuli additions were made in phase within the vertical axis.

Finally, we would like to emphasize our interest in evaluating a main involvement of lower angular frequencies

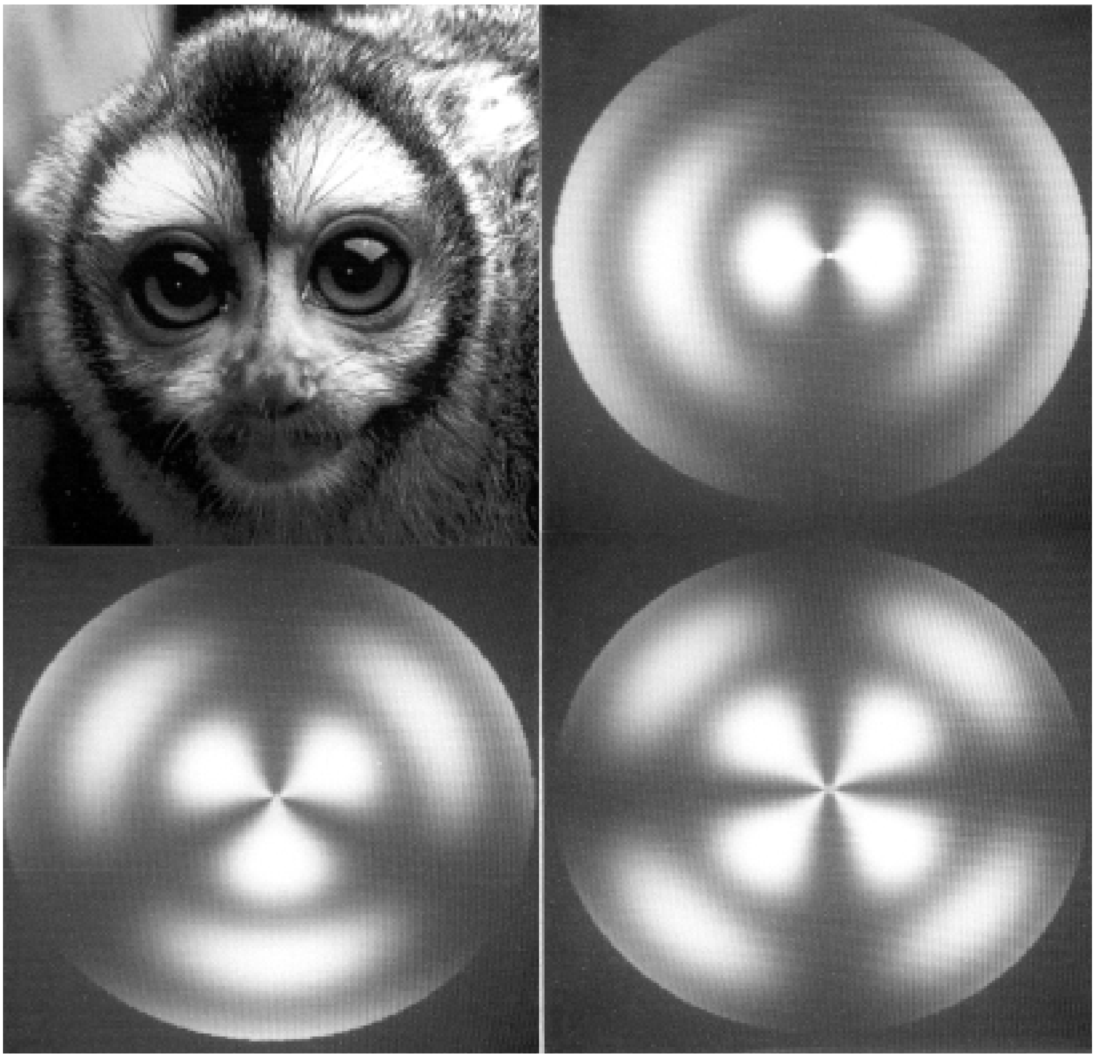

Figure 5. The coupling of low radial frequencies to 2, 3, and 4 cycles angular frequencies, as shown at top right, bottom left, and bottom right, respectively, bear some relationship to the white/black areas of the *night-monkey-aotus* (top left), even more particularly under scotopic conditions.

in face-processing, as explained in some detail in Simas and colleagues (Simas & Santos, 2002; Simas, Santos, & Theirs, 1997). We find, for instance, that the coupling of low radial frequencies to 2-, 3-, and 4-cycle angular frequencies, as shown in Figure 5, bear some relationship to the white/black areas of the *night-monkey-aotus*[1], even more particularly under scotopic conditions. While the angular frequency content of the face seems to be enhanced, the radial content is also present as shown by the black contour. The exact radial frequency to be coupled to the angular part would have to be estimated based on the monkey's face size and the more frequent distances of each other's observation. The fact that we found narrow band angular frequency filters centered at 1, 2, 3, and 4 cycles would reinforce this view. Further, cell selectivity for faces was already observed (e.g., Bruce, Desimone, & Gross, 1981) and Gallant and colleagues (Gallant, Braun, et al. 1993; Gallant, Connor, et al., 1996) found cells responding selectively to angular as well as to radial frequencies. Furthermore, Wilson, Wilkinson, and Assad (1997) found human visual system preference for a radial (frequency) organization of random-dot Glass patterns and also link these results to higher cortical visual areas as well as to face processing and prosopagnosia.

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[1] The night monkey face was found at the site http:://primates.com/monkeys/nightmonk.htm