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1st- and 2nd-order Motion and Texture Resolution in Central and Peripheral Vision

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Stimuli. **The 1st-order stimuli are moving sine gratings. The 2nd-order stimuli are fields of static visual texture, whose contrasts are modulated by moving sine gratings. Neither the spatial slant (orientation) nor the direction of motion of these 2nd-order (microbalanced) stimuli can be detected by a Fourier analysis; they are invisible to Reichardt and motion-energy detectors.** ***Method.*** **For these dynamic stimuli, when presented both centrally and in an annular window extending from 8 to 10 deg in eccentricity, we measured the highest spatial frequency for which discrimination between ±45 deg texture slants and discrimination between opposite directions of motion were each possible.** ***Results.*** **For sufficiently low spatial frequencies, slant and direction can be discriminated in both central and peripheral vision, for both 1st- and for 2nd-order stimuli. For both 1st- and 2nd-order stimuli, at both retinal locations, slant discrimination is possible at higher spatial frequencies than direction discrimination. For both 1st- and 2nd-order stimuli, motion resolution decreases 2–3 times more rapidly with eccentricity than does texture resolution.** ***Conclusions.*** **(1) 1st- and 2nd-order motion scale similarly with eccentricity. (2) 1st- and 2nd-order texture scale similarly with eccentricity. (3) The central/peripheral resolution fall-off is 2–3 times greater for motion than for texture.**

Non-Fourier Acuity Periphery Spatial frequency Motion Texture

INTRODUCTION

Mather, Cavanagh and Anstis (1985) and Chubb and Sperling (1989) examined certain stimuli that, when viewed centrally at close range, appeared to move in one direction, and when viewed peripherally or from far away, appeared to move in the opposite direction. These were composite stimuli, composed of a 1st-order component moving in one direction and a 2nd-order component moving in the opposite direction. An example of a 1st-order stimulus is a moving sine grating. An example of a 2nd-order stimulus is a patch of static visual texture, whose contrast is modulated by a moving sine grating.

The motion of 1st-order stimuli can be revealed by a Fourier analysis of the raw spatiotemporal luminance function. However, the motion components extracted by a Fourier analysis are non-informative with respect to the motion of 2nd-order stimuli (Chubb & Sperling, 1988). However, when rectified (e.g. by squaring each pixel's contrast), the motion of 1st-order stimuli can be revealed by Fourier analysis or by motion-energy computations.

The demonstrations of Mather *et al.* and Chubb and Sperling show that, as one moves away from such stimuli, one apparently loses sensitivity to the 2nd-order component faster than one loses sensitivity to the 1st-order component. This result suggests that detectability might scale differently with viewing distance for 1st- and 2nd-order motion. The current experiment measures how the discriminabilities of 1st-order motion, 1st-order texture, 2nd-order motion and 2nd-order texture scale with viewing eccentricity.

A previous attempt to observe 2nd-order motion sensitivity in the periphery was unsuccessful (Pantle, 1992). In contrast to Pantle (1992), who used relatively small patches of grating for peripheral presentations, we use annular stimuli to elicit the strongest possible peripheral signal at a well defined eccentricity. Motion and texture are clearly visible in our (peripherally viewed) stimuli.‡

METHODS

The aim was to determine the highest resolvable spatial frequency for each combination of the following three factors: (1) central vs peripheral vision, (2) 1st-order vs 2nd-order stimuli and (3) texture-slant discrimination vs motion-direction discrimination. All stimuli were presented in displays of duration 0.33 sec and with the maximum depth of modulation obtainable with the current apparatus (47%).

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‡An earlier study (Solomon & Sperling, 1991) using somewhat less adequate methodology came to a conclusion similar to that presented here.

Subjects

One of the authors (JS) and one additional trained psychophysical observer were used in this experiment. Both had corrected-to-normal vision.

Apparatus

A Leading Technologies 1230 V (12 in. diagonal) monochrome graphics monitor with a fast white phosphor using an ATVista graphics system was used to display disks and annuli with a mean luminance of 46 cd/m^2, at a refresh rate of 60 Hz.

Stimuli

The 1st-order stimuli were moving sine gratings. The 2nd-order stimuli were fields of static visual texture, whose contrasts were modulated by moving sine gratings. The static texture was binary, and randomly determined, so that 8 of every 16 pixels in a 4 × 4 array are dark and the other 8 are bright. We used maximal contrast modulation for all stimuli. For the 1st-order stimuli, this means that the pixels at the peak of the sine grating assumed the maximum luminance value; pixels at the trough of the sine grating assumed the minimum luminance value. For the 2nd-order stimuli, this means that the pixels at the peak of the sine grating assumed either the maximum or the minimum luminance values; pixels at the trough of the sine grating assumed the mean luminance value. All gratings were presented at a nominal ±45 deg texture slant.* Spatial frequency was varied by changing the number of pixels per cycle.

Central presentations were viewed from 2.0 m, and both 1st- and 2nd-order stimuli appeared as nominally circular discs, in the center of the monitor. The edges of the discs were rounded so that contrast, but not overall luminance, reduced gradually toward the edges.

Peripheral presentations were viewed from 0.38 m, and both 1st- and 2nd-order stimuli appeared as nominally circular annuli. The annuli had similarly rounded edges. Both the disc and the annulus spanned the entire vertical extent of the monitor.† Examples of our 1st- and 2nd-order stimuli appear in Fig. 1.‡

Procedure

There were two subjects, each completed 12 experimental sessions. In each session, the subject sat in a dark room and viewed the display binocularly. The only source of illumination was the light from the continuously illuminated display. Viewing distance was stabilized with a chin rest. For all sessions where central resolution was measured, the viewing distance was 2.0 m. At this distance, the stimulus disc subtended 3.9 deg of visual angle, horizontally. For all sessions where peripheral resolution was measured, the viewing distance was 0.38 m. At this distance, the stimulus annulus extended from 8.0 to 10.0 deg of visual angle, horizontally. The subject was instructed to initiate each trial with a key press after fixating on a cue spot with a mean-luminant, uniform background. Immediately after the key press, a 1st- or 2nd-order grating appeared (depending on the session), replacing the cue spot. The grating appeared in five frameblocks of four refreshes (at 60 Hz) each, followed by a mean-luminant, uniform field. The grating shifted one-quarter cycle between frameblocks. For all sessions where motion resolution was measured, the grating was presented at a −45 deg texture slant. The task was to determine whether the grating moved up and to the right or down and to the left. For all sessions where texture resolution was measured, the grating was presented at a ±45 deg texture slant. The task was to determine which of the two slants was presented. Responses were indicated with a key press, and immediate tonal feedback was given following each response.

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*For technical reasons, the display pixels were elongated vertically by a factor of 1.19; all nominal vertical dimensions must be multiplied by 1.19 to produce the true display dimensions. Thus the nominal ±45 deg gratings were actually ±50 deg, and the nominally circular window was slightly elliptical.

†For technical reasons, two unused vertical stripes necessarily flanked the stimuli. Every pixel of these stripes was set to the minimum luminance value for the entire calibration and experimental procedures. Pixels which were not part of the flanking stripes and not part of the stimulus disc or annulus, were set to the mean luminance value.

‡*Luminance calibration.* With the currently available CRT displays, it is usually not possible to manipulate the luminance of every pixel independently: given the same intensity value, horizontally adjacent pixels can be brighter than vertically adjacent pixels. To overcome this intrinsic CRT defect, every other pixel of our display, in a checkerboard pattern, was set to mean luminance. This sacrifices resolution and range of contrast (because only half the pixels contain stimulus information) in order to gain an accurate luminance transduction that is consistent over the whole range of spatial frequencies.

Using this every-other-pixel method of display, luminance calibration was accomplished visually. A two-frame, counterphasing, high spatial frequency squarewave was generated, so that when flickered at 30 Hz (the maximum obtainable temporal frequency) and viewed at a sufficient distance, it appeared to be a uniform patch. Initially, the squarewave assumed the maximum and minimum luminance values. The luminance value of the background and every other pixel was then adjusted until the flickering squarewave was indistinguishable from the background. This value (46 cd/m^2) was thus mean luminance, and assumed by every other pixel for the remainder of the calibration and experimental procedures.

The maximum contrast of the display was determined by measuring the luminance of an every-other-pixel patch of maximum luminance $L_{\max}$ and an every-other-pixel patch of minimum luminance $L_{\min}$.

$$\frac{L_{\max} - L_{\min}}{L_{\max} + L_{\min}} = 0.47.$$

One-quarter maximum luminance was determined by setting the two squarewave values to minimum and mean luminance, and then adjusting the luminance of a central uniform stripe until it became indistinguishable from the surrounding, flickering squarewave. Three-quarters maximum luminance was then determined by setting the uniform stripe to mean luminance and one of the squarewave values to one-quarter maximum luminance, and then adjusting the other squarewave value until the central stripe became indistinguishable from the flickering squarewave. Successive iterations of this procedure ensure a luminance calibration for which binary texture is balanced as accurately as possible.

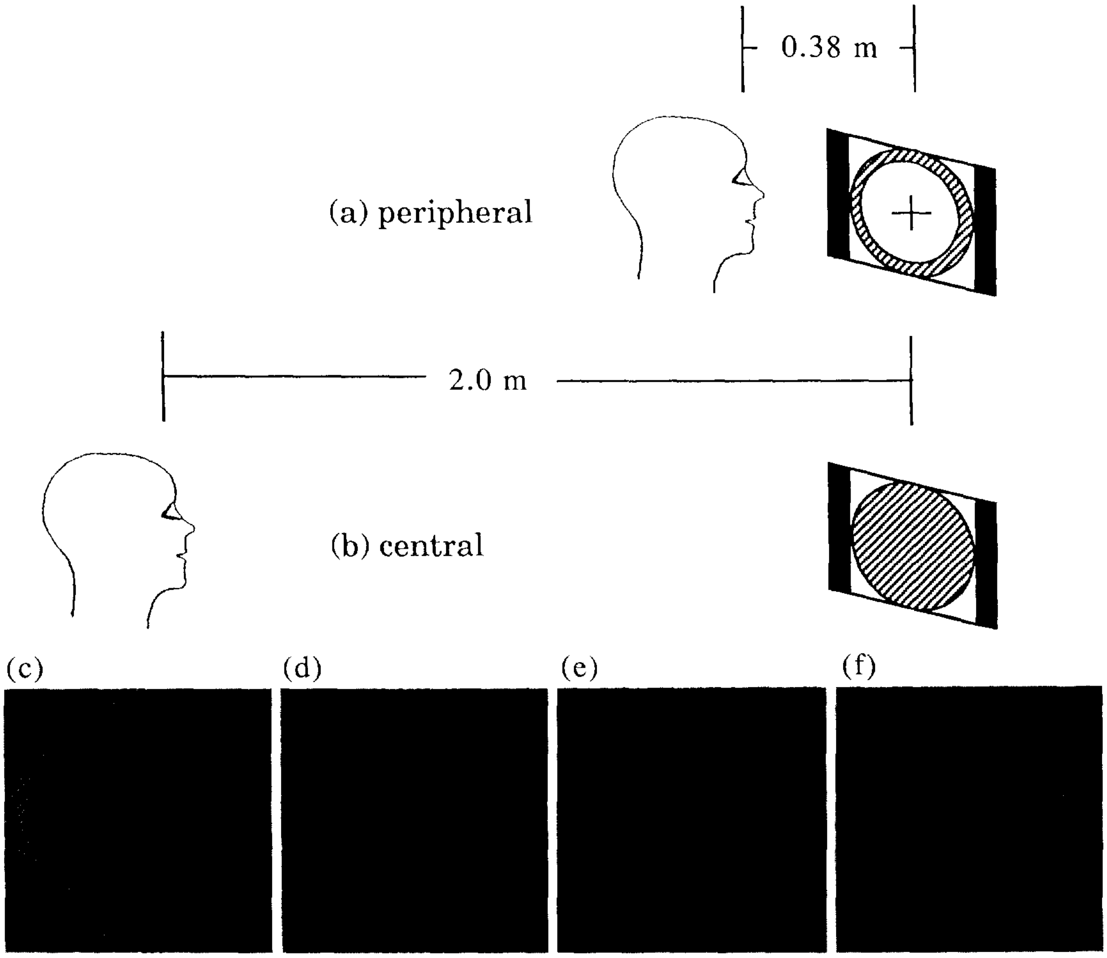

FIGURE 1. Examples of stimuli. (a) Display geometry for peripheral presentations. Fixation is in the center of the display; the static and moving test gratings are contained within the annulus, as indicated. (b) Display geometry for central presentations. (c) Central display. 1st-order stimulus. (d) Peripheral, 1st-order. (e) Central, 2nd-order stimulus (the expected luminance is equal everywhere). (f) Peripheral, 2nd-order. The experimental stimuli represented luminances extremely accurately, these reproductions should be taken only as rough indicators of what was actually presented.

Each session contained 30 trials for each spatial frequency tested. Subjects completed two sessions for each measurement using 2nd-order gratings and one session for each measurement using 1st-order gratings. The grating's spatial frequency, phase, direction of motion and, for texture measurements, slant were pseudorandomly determined on every trial. In sessions where motion resolution was measured, each spatial frequency was presented with each direction of motion equally often. In sessions where texture resolution was measured, each spatial frequency was presented with each slant equally often.

For each measurement, we used gratings of spatial frequencies which, following some initial investigations, were known to be close to the *limit of resolution* (i.e. the highest spatial frequency for which a given task is possible). These spatial frequencies are indicated in Table 1.

The maximum spatial frequency obtainable with the current apparatus, using the current procedure for peripheral presentations, was 6.08 c/deg. As we discovered, subjects could flawlessly determine the slant of the 1st-order texture at this frequency. Using gratings of 0 and 90 deg instead of ±45 deg, we were able to achieve 8.6 c/deg without otherwise altering the stimulus geometry or viewing distance. Such stimuli could move only in one-half cycle steps. We tilted the monitor to 45 deg and found that both subjects could still flawlessly determine the slant of these textures.

Using a SPARC workstation, we displayed 12.2 c/deg 1st-order gratings with an annular window which extended from 8.0 to 10.0 deg peripherally. Both subjects reported that these gratings were invisible.

RESULTS

The results are plotted in Fig. 2. Each graph shows direction and slant discrimination accuracies as functions of spatial frequency for 1 subject and 1 viewing condition.

The results are also summarized in Table 1. Limits of resolution, at accuracy rates of 75% correct, are listed in the second rightmost column. These values have been estimated by using linear interpolation. The data values used for the linear interpolations are marked with an asterisk.

There was no spatial frequency at which flawless (100% correct) peripheral 2nd-order direction

TABLE 1. Results

Subject	Task	Stimulus	Eccentricity (deg)	Spatial frequency (c/deg)	Performance (% correct)	Est. limit of resolution (c/deg)	Scale factor
JB	Direction discrimination	1st-order	0–3.9	7.68	100		6.1
				10.2	97*	15.0	
				15.4	73*		
				30.7	50		
			8.0–10.0	1.52	100		
				2.02	93*	2.45	
				3.05	35 (50)*		
		2nd-order	0–3.9	1.92	85*	2.28	5.3
				2.71	63*		
				3.84	43		
			8.0–10.0	0.160	75		
				0.269	83		
				0.380	80*	0.432	
				0.537	65*		
				0.760	67		
				1.21	53		
				1.52	45		
	Slant discrimination	1st-order	0–3.9	15.4	100*	23.5	2.3
				30.7	53*		
			8.0–10.0	6.08	100		
				8.60	(100)*	10.4	
				12.2	(50)*		
		2nd-order	0–3.9	2.71	97		2.0
				3.84	82*	5.08	
				6.14	69*		
				7.68	60		
			8.0–10.0	1.22	100		
				1.52	98		
				2.03	83*	2.57	
				3.04	68*		
JS	Direction discrimination	1st-order	0–3.9	10.2	100		4.5
				15.4	100*	23.1	
				30.7	50*		
			8.0–10.0	2.02	100		
				3.05	100*	5.10	
				6.08	63*		
		2nd-order	0–3.9	1.92	100		6.3
				2.71	78*	2.87	
				3.84	57*		
			8.0–10.0	0.160	82		
				0.269	78		
				0.380	82*	0.453	
				0.537	67*		
				0.76	67		
				1.21	63		
				1.52	53		
	Slant discrimination	1st-order	0–3.9	15.4	100*	24.3	2.3
				30.7	57*		
			8.0–10.0	6.08	100		
				8.60	(100)*	10.4	
				12.2	(50)*		
		2nd-order	0–3.9	3.84	100		3.4
				6.14	87		
				7.68	82*	8.61	
				10.2	63*		
				15.4	50		
			8.0–10.0	1.22	100		
				1.52	95		
				2.03	83*	2.53	
				3.04	67*		

*Linear interpolation between these values yeilded the estimated limits of resolution.

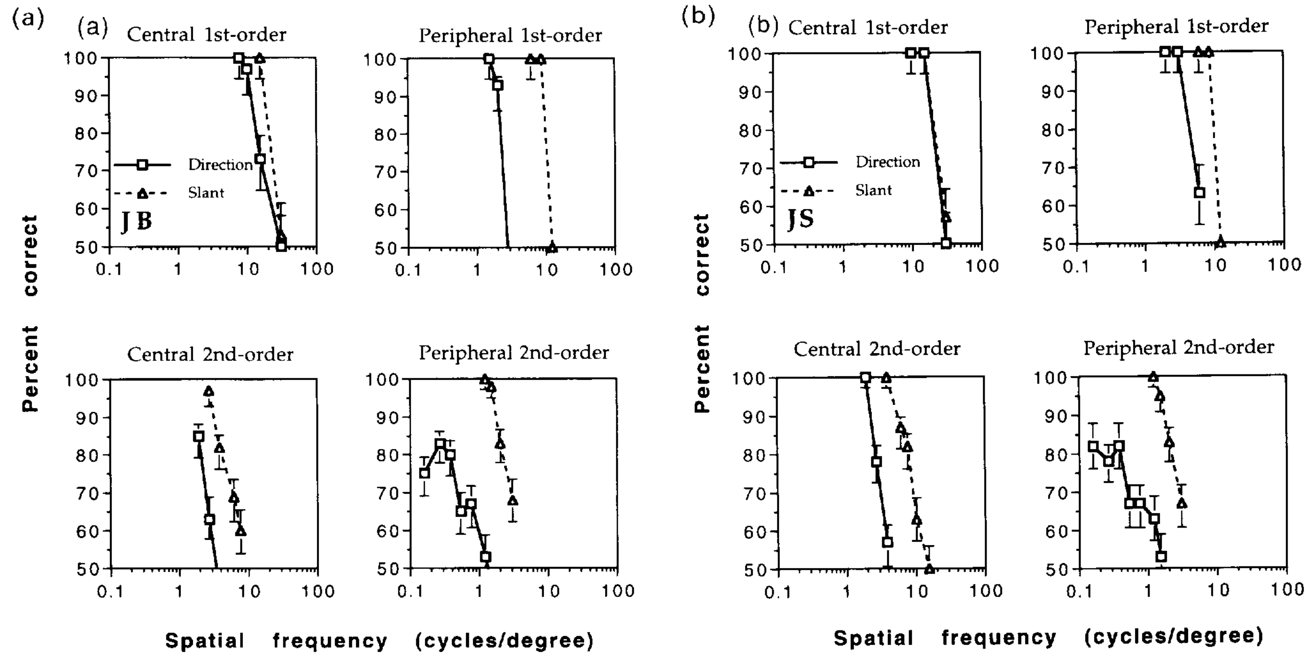

FIGURE 2. Results. Each graph shows measured accuracies for direction and slant discrimination as functions of spatial frequency for 1 subject and 1 viewing condition. Error bars contain the 64% confidence intervals for the true accuracies.

discrimination was recorded. And in accordance with Pantle (1992), the motion of these contrast-modulated noise gratings was below threshold at spatial frequencies 0.5 c/deg and above. However, at spatial frequencies below 0.5 c/deg, accuracy met or exceeded 75% correct for both subjects. Subjects reported that these stimuli appeared to move on all trials, however direction was not always determinable. Subjects made no conscious effort to correlate position of the grating with elapsed time within the 0.33 sec displays.

Note that JB reported only 75% correct at the lowest spatial frequency (0.160 c/deg) in the peripheral 2nd-order motion sessions. His performances were more accurate at the next two higher spatial frequencies. Although the contrast sensitivity function for direction discrimination of 2nd-order gratings may indeed be non-monotonic, we believe that in this case, the apparently non-monotonic relationship between performance and spatial frequency is an artifact of the stimulus geometry used in the peripheral presentations. Receptors tuned to spatial periods greater than the width of the annulus are unable to receive as much stimulation as those tuned to spatial periods less than the width of the annulus. Informal observations indicate that performance continues to drop as spatial frequency is reduced below 0.160 c/deg. Consequently, we estimated the limit of resolution using performances at higher spatial frequencies.

Note also that JB's performance at the highest spatial frequency (3.05 c/deg) in the peripheral 1st-order motion session was significantly below chance level. For the purpose of estimating the limit of resolution we have considered this performance to be *at* the chance level (50%).

The value of 10.4 c/deg was used as the estimate for the limit of 1st-order texture resolution in the periphery. This value is based on the informal observations which are detailed above (Procedure). Interpolating linearly between flawless performance at 8.06 c/deg and chance level performance at 12.2 c/deg yields an estimate of 10.4 c/deg for a 75% correct performance.

For all types of stimuli and both retinal locations, both subjects could perform the texture-slant discrimination task at higher spatial frequencies than the motion-direction discrimination task.

The estimate of the central/peripheral scale factor is the ratio: (highest resolvable frequency in central vision) divided by (highest resolvable frequency in peripheral vision). These ratios, for each type of stimulus and task, are listed in the rightmost column of Table 1. The main finding is that scale factors between 1st- and 2nd-order stimuli are quite similar, irrespective of task (motion or texture) and subject. At most (JS's performance on the slant discrimination task) they differ by 40%. A second finding is that the estimated scale factors for the slant discrimination task are systematically much lower than the estimated scale factors for the direction discrimination task for both stimuli.

The various central/peripheral scale factors, and the relations between them, are summarized in Table 2. The bottom row of Table 2 shows ratios of ratios. These quantities describe how 1st-order frequency thresholds scale with eccentricity relative to how 2nd-order frequency thresholds scale with eccentricity. A ratio of 1.0 indicates that 1st- and 2nd-order motion (or texture) resolution scale identically with viewing eccentricity. All four ratios are reasonably close to 1.0.

The entries under the column heading "motion/texture" describe how motion frequency thresholds scale relative to how texture frequency thresholds scale. These ratios indicate that motion resolution falls off between 2 and 3 times faster with eccentricity than

TABLE 2. Comparison of 1st- and 2nd-order central/peripheral scale factors*

	JB			JS		
Stimulus	Motion	Texture	Motion/texture	Motion	Texture	Motion/texture
1st-order	6.1	2.3	2.7	4.5	2.3	2.0
2nd-order	5.3	2.0	2.7	6.3	3.4	1.9
1st/2nd	1.2	1.2	1.0	0.7	0.7	1.1

*(Highest resolvable frequency in central vision)/(Highest resolvable frequency at 8–10 deg eccentricity).

texture resolution does. This finding is consistent for both subjects and independent of whether the stimuli are 1st- or 2nd-order gratings.

DISCUSSION

Watson (1987) proposed a method for the estimation of local spatial scale. This is the so-called shift rule. When two contrast sensitivity functions, obtained at different retinal eccentricities are plotted on log–log coordinates, the shift rule states that the horizontal shift required to bring the two functions into symmetry corresponds to the ratio of local spatial scales.

Measurement of complete contrast sensitivity functions proved not to be feasible with the current apparatus. Instead, we obtained an estimate for one point on each of eight contrast sensitivity functions, for each subject. This point, the highest spatial frequency for which two-alternative accuracy drops to 75% at the maximum available contrast in our display, we have termed the limit of resolution. Assuming that the contrast sensitivity functions for centrally and peripherally presented stimuli are of the same shape, our estimates of local spatial scale, based on the limits of resolution, would be consistent with those derived from the shift rule.

For our 1st-order stimuli, we believe that the contrast sensitivity functions for centrally and peripherally presented stimuli should be of very similar shape. Several authors have used the shift rule (e.g. Watson, 1987; Whitaker, Rovamo, MacVeigh & Makela, 1992) for 1st-order stimuli, and have determined similar scale factors for similar eccentricities. The scale factors that are estimated by our procedure are also in good agreement with the cortical magnification factor for 9 deg, which ranges from 3.6 to 4.9, depending on location in the visual field (Rovamo & Virsu, 1979).

For the 2nd-order stimuli, we can only speculate as to the shapes of the contrast sensitivity functions for centrally and peripherally presented stimuli. For the time being, the limits of resolution are the best indices for comparison that we have.

Our results do not explain why the perception of motion is often impossible when one views a small patch of a drifting, 2nd-order grating peripherally. A similar phenomenon does not occur with 1st-order gratings. However, the current results preclude one hypothesis. Because 1st- and 2nd-order motion resolution scale similarly with eccentricity, the aforementioned, qualitative difference between 1st- and 2nd-order motion perceptions cannot be due to a scaling difference in the sizes of the smallest processing units for the two stimuli. It remains possible that the areas of summation for the two stimuli scale differently with eccentricity. Our methods were designed to maximally exploit the spatial summation abilities of both the 1st- and 2nd-order systems. Another possibility is that the internal noises of the 1st- and 2nd-order pathways scale differently with eccentricity.

CONCLUSION

Second-order motion *can* be perceived in peripheral vision. Moreover, for both motion-direction discrimination and for texture-slant discrimination, first- and second-order perceptual processing scale similarly with eccentricity. However, between the fovea and 8–10 deg eccentricity, motion sensitivity (for both 1st- and 2nd-order stimuli) falls off 2–3 times more quickly than does texture sensitivity.

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