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Gender differences in response to spatial frequency and stimulus orientation

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Male and female subjects with normal or corrected-to-normal visual acuity and less than .25 diopter of corrected astigmatism were asked to make contrast threshold judgments in response to both stationary and drifting grating displays. Results indicate a sex difference in contrast sensitivity as a function of spatial frequency for vertical and oblique orientations.

Recent data demonstrate sex differences in several modalities of human sensory abilities. These have been reviewed by McGuinness (1976) and McGuinness and Pribram (1979). Most relevant to this study are differences in visual processing. Several investigators report males to have better static and dynamic acuity (Burg, 1966; Burg & Hulbert, 1961; Roberts, 1964). McGuinness (1976) and McGuinness and Lewis (1976) administered a battery of visual tasks to a sample of young adults and found males to be significantly more sensitive at photopic levels for tests of acuity, tolerance of brightness, and visual persistence. Females were found to have superior scotopic thresholds for 20° of visual angle and greater scotopic persistence. Ross and Woodhouse (Note 1), using children ranging in age from 5 to 7 years, confirmed the male superiority in acuity for younger age groups and also found a higher ratio between horizontal and oblique acuity (anisotropy) in males only.

Differences in response to several visual illusions involving motion sensitivity have also been reported. Immergluck and Mearini (1969) found boys to have a higher reversal rate for reversible figures and Pohl and Caldwell (1968) found females to have a higher threshold for the phi phenomenon of apparent motion. Johannsson (Note 2) reports that females exaggerate motion track enlargement in a sample of young adults.

While these data have been accumulating, the application of Fourier theory to information processing has introduced a new dimension to visual theory and permitted the analysis of stimulus patterns into component spatial frequencies. In turn, these frequencies have been found to affect psychophysical response measures (Campbell & Robson, 1968; Nachmias, Sachs, & Robson, 1969; also see Sekuler, 1974, for a comprehensive review). Campbell and Robson (1968) found the contrast threshold for a grating of light and dark bars to be determined by the fundamental component of the particular waveform used to generate the display. Blakemore and Campbell (1969) report that adaptation to a square-wave grating reduces subsequent response to both the sinusoidal fundamental and third harmonic components when these were presented separately as test gratings. The coding of the retinal image is suggested to occur through the operation of centrally located mechanisms, each having optimal sensitivity to a particular spatial frequency (Blakemore & Campbell, 1969).

Stimulus orientation has also been found to affect measures of perception, and numerous studies report anisotropy in human vision such that resolution is superior for vertical and horizontal targets (Attneave & Olson, 1967; also see Appelle, 1972, for a comprehensive review; Emsley, 1925; Jastrow, 1893; Ogilvie & Taylor, 1958). Analogous to the tuning found in the frequency domain, a 30° to 40° shift in orientation of a diagonal line will significantly improve its perceptibility while a shift of the same amount will reduce discrimination for vertical and horizontal lines (Finger & Spelt, 1947). Optical explanations of the phenomenon have not been supported, and the experimental results of Campbell, Kulikowski, and Levinson (1966) strongly suggest a postretinal origin of orientation preference.

Neurological studies yield complementary data and reveal functional organizations through which mechanisms receptive to specific parameters of visual information may operate (Campbell, Cooper, & Enroth-Cugell, 1969 Enroth-Cugell & Robson, 1966; Hubel & Wiesel, 1962). Ikeda and Wright (1974a) describe the response characteristics of two types of cortical cells selective for spatial frequency. The "transient" cell is distinguished by large receptive field size and peak sensitivity to gratings of low spatial frequency, while the slower conducting "sustained" cell has a smaller receptive field size and optimal response to high-frequency gratings. Evoked

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responses from these units are severely diminished if the stimulus differs by a factor of two from the preferred frequency for the cell (Campbell & Robson, 1968).

Similarly, Hubel and Wiesel (1962) report the discovery of orientation-specific cells at the cortical level with each unit maximally responsive to a particular orientation of the stimulus in its receptive field. Comparable to the limited tuning found among the frequency analyzers, response is significantly decreased if the target is shifted 10° to 15° from the cell's preferred orientation (Hubel & Wiesel, 1965). Campbell and Kulikowski (1966) propose that information from the retinal image is transferred through independent orientation-specific channels and the content of these further analyzed in the frequency domain.

Most of these psychophysical and physiological studies restrict investigation to a small population (usually male). Hence, normative data are lacking. This problem becomes especially critical as the increasing number of gender effects in visual processing are revealed. If different sensory threshold levels, mediated through physiological mechanisms, are responsible for differentially biasing information processing between the sexes, it is conceivable that the structuring of their respective perceptual systems may be affected as a consequence. If a cohesive theory of psychophysical sex differences is to emerge from the scattered results obtained in previous studies, systematic investigation of response differences as a function of the spatial frequency and orientation-specific mechanisms is highly recommended.

In an attempt to isolate and quantify some of these variables, the following set of experiments was designed to examine response characteristics as a function of spatial frequency, stimulus orientation, and stimulus motion. Young adults screened for acuity and astigmatism were tested on contrast threshold for 13 spatial frequencies ranging from .4 to 10 cycles/deg. These were presented in one of four orientations as stationary targets. In a second experiment, these subjects were tested again using the same stimulus parameters with the exception that the stimulus target was moving at a constant phase velocity (drift).

EXPERIMENT 1

Method

Subjects. Subjects were 39 undergraduate students (20 males and 19 females) who participated in the study for course credit. All subjects were required to possess, or be corrected to, 20/20 acuity or better as measured by a Snellen chart. Astigmatism levels were determined by test frame refraction for all subjects, and prescriptions for those wearing corrective lenses were determined by a lensometer (Toko Model 1B). Subjects were eliminated from the study if the correction required for astigmatism exceeded .25 diopter by either measure.

Apparatus. The stimulus, a uniform grating pattern, was generated using a method similar to that described by Campbell and Green (1965), and presented on a monitor, Tektronix Type 604. Beam intensity (z axis) of the 13 × 10.5 cm screen was modulated with a pure sinusoidal frequency produced by a function generator (ASG Model 200), and, with suitable synchronization of the time base and raster scan generators, stable gratings of any spatial frequency could be displayed. Separate controls were provided for adjusting contrast and spatial frequency, independent of mean screen luminance, which measured at output with a digital photometric microscope (Gamma Scientific Models 2400 and 700-10-A) at a constant 19.19 cd/m^2 for 13 gratings (.4, .6, .8, 1.0, 2.0, 3.0, 4.0, 5.0, 6.0, 7.0, 8.0, 9.0, and 10.0 cycles/deg). Contrast is defined as $(Lmax - Lmin)/(Lmax + Lmin)$, where Lmax and Lmin are the maximum and minimum luminance levels in the grating, and could be adjusted by turning the knob of a potentiometer and attenuator in series. The monitor itself was fixed in a jig which allowed the experimenter to manually rotate the display face to one of four positions: 45° (right oblique), 90° (horizontal), 135° (left oblique), and 180° (vertical).

Procedure. After being tested for acuity and astigmatism, each subject was seated at a distance of 160 cm from the screen and positioned by means of a chinrest and two foam padded restrainers at each side of the head. The screen was viewed binocularly and ametropic observers wore their normal refractive corrections for all measurements.

Trials were blocked by orientation and counterbalanced across subjects. Subjects made contrast threshold judgments, using an ascending method of limits, for each of the 13 spatial frequency gratings presented randomly within each orientation. Each subject was tested for 45 min during two separate sessions, usually 2-3 days apart. Each session consisted of 96 trials presented in six blocks of 16 trials each, which included practice trials. To avoid unnecessary assumptions about response criteria, 2-3 blank ("catch") trials were included within each block during which no stimulus was presented.

At the beginning of each session, the subject was told to look at the center of the screen and that he/she would be seeing a series of stripes of varying widths which would be continuously present and gradually be increased in contrast until visible. He/she was instructed that the task was to respond with a "yes" as soon as the presence of a grating was detected ("see the stripes") and to withhold response if no grating was seen. The subject was told about the catch trials, and accuracy was stressed.

Each block of trials took approximately 5 min to complete and was run under mesopic conditions, during which the experimental room was illuminated by pilot lights from the equipment and a small light source near the experimenter. In between each block, the subject was given a 1-2-min rest period, during which room luminance was increased to a photopic level.

Results

Most subjects were extremely accurate in avoiding false positives on the catch trials, with an error rate below 20% of the 18 catch trials. However, three subjects with error rates well above this value were eliminated, leaving data for a total of 36 subjects, 18 male and 18 female.

A separate analysis of variance was carried out for 45° and 135° conditions within each sex; it showed no significant differences between these two orientations [$F(1,442) = .001$, $p < 1.0$, for males; and $F(1,442) = 1.065$, $p < 1.0$, for females]. Scores for the oblique orientations were then collapsed into one measure for each sex in all subsequent analyses.

Contrast threshold means are shown in Table 1. A 2 (sex) by 3 (orientation) by 13 (frequency) analysis

Table 1
Experiment 1: Mean Contrast Threshold (Percent) as a Function of Spatial Frequency and Orientation

Group	Spatial Frequency (Cycles/Degree) .4	.6	.8	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Mean	SD
								Males							
Vertical	1.92	1.54	1.20	.93	.72	.70	.74	.83	.97	1.01	1.35	1.65	1.91	1.21	.22
Horizontal	1.86	1.51	1.13	.95	.74	.73	.75	.86	.95	1.11	1.40	1.67	1.96	1.21	.23
Oblique	1.92	1.54	1.21	.96	.75	.77	.85	.94	1.15	1.32	1.57	1.88	2.14	1.30	.23
Mean	1.90	1.53	1.18	.95	.73	.73	.78	.88	1.02	1.15	1.44	1.73	2.00		
SD	.25	.36	.24	.17	.12	.14	.14	.16	.22	.24	.29	.28	.32		
								Females							
Vertical	1.73	1.42	1.16	.94	.73	.76	.81	.89	1.07	1.30	1.55	1.70	2.06	1.26	.25
Horizontal	1.78	1.41	1.21	1.00	.73	.71	.79	.85	.97	1.14	1.45	1.73	1.94	1.21	.20
Oblique	1.69	1.37	1.12	.93	.77	74	.85	.96	1.15	1.40	1.71	2.00	2.37	1.31	.28
Mean	1.73	1.40	1.16	.96	.74	.74	.82	.90	1.06	1.28	1.57	1.81	2.12		
SD	.23	.32	.28	.20	.09	.10	.11	.16	.21	.29	.37	.35	.44		
Total Mean	1.82	1.46	1.17	.95	.74	.74	.80	.89	1.04	1.24	1.51	1.77	2.06		
Total SD	.24	.34	.26	.18	.11	.12	.33	.16	.21	.27	.33	.31	.38		

Note—*Contrast = 100(Lmax − Lmin)/(Lmax + Lmin).*

of variance was carried out. The summary of results appears in Table 2, where it can be seen that the main effect of sex is not significant [F(1,34) = .135, p < 1.0], while orientation and spatial frequency are highly significant main effects [F(2,68) = 18.80, p < .001; F(12,408) = 264.16, p < .001]. Further analysis, using the Scheffé method for multiple post hoc comparisons, revealed resolution to be superior for both the vertical and horizontal gratings across subjects, confirming the anisotropy effect found in previous research [F′(2,24) = 9.80, p < .025]. Differences in degree of anisotropy were not found to be significant in between-sex comparisons.

Table 1 presents the mean scores for each frequency at each orientation. Threshold was considerably higher for the oblique orientation, explaining some of the variance obtained in the orientation/spatial-frequency interaction. The mean scores in Table 1 also show that anisotropy is absent at low spatial frequencies and increases with high spatial frequencies.

Of particular interest to this study is the significant two-way Sex by Spatial Frequency interaction [F(12,408) = 2.563, p < .01]. Scheffé comparisons of means showed females to be superior in the resolution of the three lowest frequency gratings (.4, .6, .8 cycles/deg) and males to be better in the highest frequencies (8.0, 9.0, 10.0 cycles/deg) [F′(1,34) = 42.4, p < .001, respectively]. The mid range showed no gender difference. This interaction is most clearly illustrated by Figure 1, which plots the difference scores (female-male) for contrast threshold as a function of spatial frequency. This effect was considerably more pronounced for vertical and oblique orientations than for the horizontal condition, and this accounts for some of the variance contributed by the significant three-way interaction.

Table 2
Experiment 1: Analysis of Variance Summary

Effect	df	F
Sex	1,34	.135
Orientation	2,68	18.802†
Spatial Frequency	12,408	264.165†
Sex/Orientation	2,68	.649
Sex/Spatial Frequency	12,408	2.563**
Orientation/Spatial Frequency	24,816	6.637†
Sex/Orientation/Spatial Frequency	24,816	1.543*

**p < .05. **p < .01. †p < .001.*

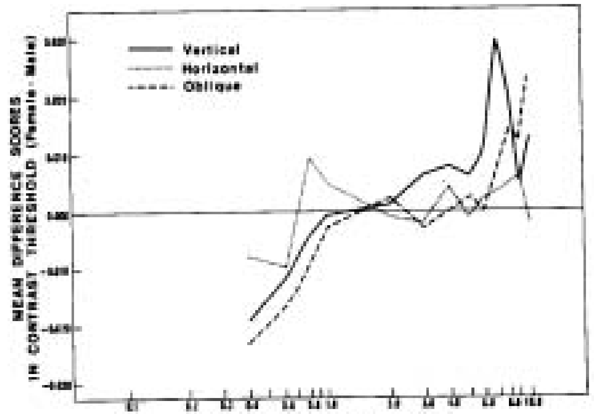

Figure 1. Stationary target difference scores for three orientations. Negative values indicate females superior, positive values indicate males superior.

EXPERIMENT 2

Method

The same subjects who participated in Experiment 1 also took part in Experiment 2. Both the apparatus and procedure also remained the same, with one exception. In Experiment 2, the

Table 3
Experiment 2: Mean Contrast Threshold (Percent) as a Function of Spatial Frequency

Group	.4	.6	.8	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	Mean	SD
	Spatial Frequency (Cycles/Degree)														
								Males							
Vertical	1.05	.92	.77	.72	.68	.69	.75	.83	1.05	1.16	1.41	1.59	2.00	1.05	.21
Horizontal	1.02	.92	.81	.75	.69	.72	.77	.91	.98	1.15	1.45	1.77	1.87	1.06	.20
Oblique	1.02	.92	.80	.73	.69	.71	.83	.94	1.11	1.27	1.54	1.86	2.12	1.12	.18
Mean	1.03	.92	.79	.73	.69	.71	.78	.89	1.05	1.19	1.47	1.74	2.00		
SD	.22	.16	.12	.13	.11	.13	.14	.18	.21	.23	.29	.35	.29		
								Females							
Vertical	.87	.81	.74	.68	.63	.69	.79	.93	1.12	1.31	1.54	1.70	2.17	1.08	.21
Horizontal	.97	.83	.80	.69	.67	.68	.75	.85	1.01	1.18	1.50	1.73	2.05	1.05	.19
Oblique	.99	.85	.79	.71	.68	.74	.83	.94	1.16	1.43	1.81	2.14	2.39	1.19	.25
Mean	.94	.83	.78	.69	.66	.70	.79	.91	1.10	1.31	1.62	1.86	2.20		
SD	.19	.13	.09	.07	.08	.10	.11	.17	.25	.31	.34	.42	.55		
Total Mean	.99	.88	.79	.71	.67	.71	.79	.90	1.07	1.25	1.54	1.80	2.10		
Total SD	.21	.14	.11	.10	.19	.11	.12	.17	.23	.27	.31	.39	.42		

Note—*Contrast* = *100(Lmax − Lmin)/(Lmax + Lmin).*

gratings were set to drift across the display face of the monitor at a constant phase velocity of approximately 10 deg/sec.

Results

A separate analysis of variance on the 45° and 135° conditions within each sex showed no significant differences to exist between these two orientations [$F(1,442) = .112$, $p < 1.0$, for males; and $F(1,442) = .83$, $p < 1.0$, for females]. As in the previous set of data, scores for the oblique orientations were then collapsed into one measure for each sex in subsequent analyses.

Mean scores for contrast threshold are illustrated in Table 3. A Sex by Orientation by Spatial frequency analysis of variance was carried out, and a summary of results appears in Table 4. Again, orientation and spatial frequency emerge as highly significant main effects [$F(2,68) = 16.776$, $p < .001$; and $F(12,408) = 318.113$, $p < .001$, respectively]. While sex did not appear as a significant main effect [$F(1,34) = .518$, $p < 1.0$], the two-way interaction of Sex by Spatial Frequency was highly significant [$F(12,408) = 3.399$, $p < .001$]. As in Experiment 1, Scheffé post hoc comparisons found females to have lower contrast thresholds for the two lowest frequencies (.4-.6 cycle/deg) while males had lower thresholds for the highest four frequencies (7-10.0 cycles/deg) [$F'(1,34) = 45.2$, $p < .001$; and $F'(1,34) = 117.90$, $p < .001$, respectively]. This effect was considerably more pronounced in the vertical and oblique conditions. These difference scores are illustrated in Figure 2.

Table 4
Experiment 2: Analysis of Variance Summary

Effect	df	F
Sex	1,34	.518
Orientation	2,68	16.776*
Spatial Frequency	12,408	318.113*
Sex/Orientation	2,68	1.965
Sex/Spatial Frequency	12,408	3.399*
Orientation/Spatial Frequency	24,816	5.635*
Sex/Orientation/Spatial Frequency	24,816	1.407

*$p < .001$.

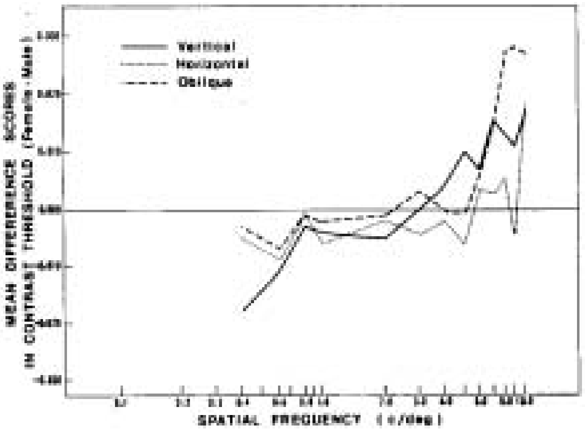

Figure 2. Drifting target difference scores for three orientations. Negative values indicate females superior, positive values indicate males superior.

In order to compare the two conditions, total mean scores (data collapsed across sex) were computed from the 1,150 scores for each spatial frequency. The curves, illustrated in Figure 3, have been plotted by connecting these mean values. It can be seen that threshold functions in the two stimulus conditions are different for low spatial frequencies. Maximum sensitivity to drifting stimuli is elevated across the entire low to mid spatial frequency range and includes .4 to 4.0 cycles/deg. Sensitivity is particularly increased from .4 to 1.0 cycles/deg.

Anisotropy effects occur similarly in both conditions of static and drifting targets, with anisotropy found

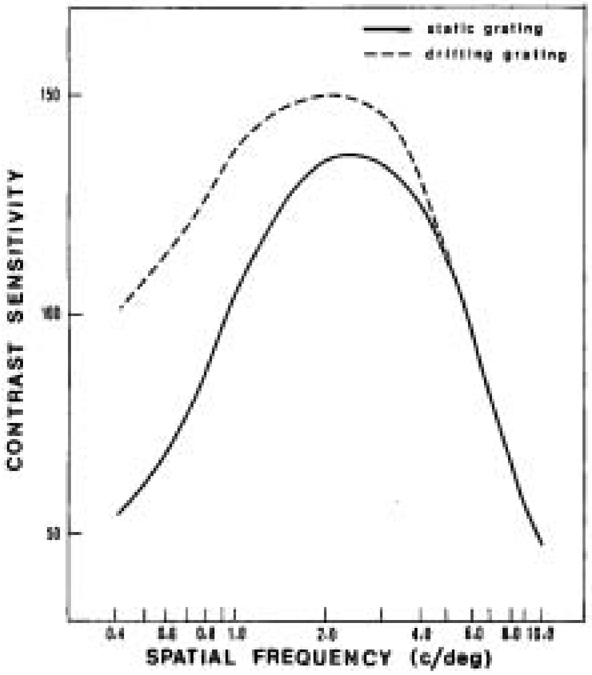

Figure 3. Contrast sensitivity (the reciprocal of contrast threshold). Combined means collapsed across orientation and sex for static and drifting targets.

only in the mid to high spatial frequency range and increasing with higher frequencies (see Tables 1 and 3).

DISCUSSION

The results for the main effects of spatial frequency and orientation confirm findings from other laboratories. Contrast thresholds are lowest at 2-3 cycles/deg of visual angle for stationary targets, and show a curvilinear function. Low-contrast threshold function changes in conditions of motion, such that thresholds are lower across the entire low to mid range of spatial frequencies. At about 4 cycles/deg, these curves approximate those found in response to stationary targets.

Anisotropy is found in both static and drift conditions and occurs only in mid range to high spatial frequencies, increasing noticeably with higher spatial frequency targets.

These data tend to indicate that there are at least two qualitatively different processes involved in the visual system. Sensitivity to motion is part of a low spatial frequency mechanism, and anisotropy is a part of the high spatial or acuity mechanism.

Above and beyond these two different systems are the sex differences which are pronounced at the outer regions of the contrast sensitivity curve, with females significantly more sensitive in the low spatial frequency range and males more sensitive to high spatial frequency targets. These sex differences are not affected by any manipulation of the stimulus such as orientation and motion, and thus appear to be robust differences reflecting something other than motion sensitivity or effects attributable to anisotropy. Also, contrary to the data of Ross and Woodhouse, females are, if anything, *more* anisotropic than males (see Tables 1 and 3).

Therefore, a further explanation for the meaning of these sex differences must be sought. An appealing hypothesis is one of *temporal* differences in processing between low and high spatial frequencies. Ikeda and Wright (1974a, 1974b) proposed that different frequency range sensitivities reflect a dichotomous processing system in which information from the retinal image is transferred through independent channels, that is, through the transient and sustained cell mechanisms. The transient system is rapid and sensitive to low spatial frequencies. The sustained system is slow and sensitive to high spatial frequencies. A similar conclusion was reached from the results of a masking study on human observers by Vassilev and Mitov (1976), in which a threefold effect of temporal masking occurred between low and high spatial frequency targets of 3 and 10 cycles/deg.

Thus, neurophysiological and psychophysical studies show two temporal domains in visual processing with fast intake of low-frequency information and slower processing of higher frequency information. As the mid range of frequencies showed no sex difference, it is suggested that the differences obtained would be exaggerated by the extension of the upper and lower limits of the frequency distribution. Further research, examining response variation as a function of temporal characteristics of the two systems, is strongly suggested on the basis of results obtained in this study.

These data also have implications for pattern recognition. Ginsburg (1971) found global analysis of patterns dependent upon the utilization of low spatial frequency information, while attention to high-frequency components tends to segregate a pattern, working against Gestalt organization. We suggest that females, with primary sensitivity to low-frequency information, may take an "integrative" approach to pattern analysis, while males may take a "segregative" approach, attending primarily to high-frequency information isolating objects of interest from the field. Further examination of sex differences on measures of temporal integration and recognition of patterns is recommended before this can be achieved.

Both sexes showed less sensitivity to diagonally oriented gratings. The mammalian visual system may have adopted the strategy of primary tuning to vertical and horizontal orientations in order to provide an intrinsic frame of reference, analogous to the crosshairs in the sighting mechanism of a telescope. Obliquely oriented objects would then achieve perceptual significance in their relationship to the primary axes.

The findings that the sex difference exhibited in the frequency domain is considerably weaker for horizontal gratings is difficult to explain. It could be that both sexes perceive "ground" with equal facility in a world ordered into horizontal planes, and that perceptive differences begin to operate only in the processing of stimuli referent to this ground.

Differential patterns of horizontal eye movements between the sexes may be involved, with females using more frequent or more rapid saccades. This would tend to smear high frequencies in the vertical and oblique conditions due to temporal summation in the eye. It would also serve to accentuate the visibility of low-frequency gratings due to the motion of the image across the retina. This hypothesis suggests that (1) females would have lower contrast thresholds for low spatial frequencies, (2) they would have higher thresholds for high frequencies, and (3) horizontal gratings would not show effect 1 and 2. These three predictions are supported by the data, but the fact that the maximum sex difference was observed in the oblique rather than vertical grating condition suggests that the differential horizontal eye-movement interpretation provides only a partial explanation of the results. Further investigation of differences in eye movements between the sexes is suggested before this issue can be resolved.

The results of these experiments indicate that fundamental mechanisms responsible for visual processing may operate with a differential bias between the sexes. Based upon neurophysiological models, several directions are indicated for future research.

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