ABSTRACT

COLLINEARITY AND SURROUND SIZE EFFECTS ON SPATIAL DISCRIMINATION TASKS

by Michael Lawrence Kramer

The present study was performed to better understand the effects of spatial characteristics of surrounds on suprathreshold spatial discrimination tasks. The tasks used were hyperacuity orientation (centered around vertical) and spatial frequency (centered around 4 cpd) discriminations between 40-minarc, circular center patches of sinusoidal grating. Surrounds were vertical, sinusoidal grating rings at exactly 4 cpd, with a ring width of 20-minarc. Surround size and location was modulated using BOW-TIE style stimuli (Cannon & Fullenkamp, 1991) in order to specifically test how collinearity (or its lack) affects fine spatial discriminations. Discriminability was measured using $d'$ values (obtained from a 6 point response scale). Our results suggest that collinear surround locations have a stronger inhibitory effect on these discrimination tasks when compared to non-collinear side-flank surround locations of equal size. Increasing surround coverage area created a stronger inhibitory effect or caused no significant change depending on the location.
COLLINEARITY AND SURROUND SIZE EFFECTS ON SPATIAL DISCRIMINATION TASKS

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Michael Lawrence Kramer
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Advisor______________________________
Dr. Lynn A. Olzak

Reader_______________________________
Dr. Allan Pantle

Reader_______________________________
Dr. Greg Reese
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BACKGROUND AND INTRODUCTION

In the neuroscience literature, the classical receptive field (CRF) of a cell has been defined as the area on the retina where the presentation of visual stimuli may excite the cell (see Mizobe et al., 2001 and Levitt & Lund, 2002 for more detailed reviews). Although presentation of stimuli to areas outside of the CRF for a given cell does not invoke responses on its own, it has been shown that stimuli outside of the CRF are able to modulate the response of the cell if it is already firing (Allman, Miezen, & McGuinness, 1985; Cavanaugh, Bair, & Movshon, 2002; DeAngelis, Ohzawa, & Freeman, 1993; Nelson & Frost, 1978). Similar surround modulation in psychophysical tasks has been shown as well (Chubb, Sperling, & Solomon, 1989; Olzak & Laurinen, 1999; Xing & Heeger, 2000). The areas outside of the CRF that are able to modify a cell’s response will be referred to as the modulatory receptive field (MRF) of the cell. The modulations produced by stimulation of the MRF have been shown to be both excitatory and inhibitory depending on the circumstances (Angelucci et al., 2002; Walker, Ohzawa, & Freeman, 2002). Knierim & Van Essen (1992) proposed that inhibitory modulations could be used for the segregation of textures, while Field, Hayes, & Hess (1993) hypothesized that excitatory modulations might be part of a general contour integration mechanism. It is important to determine how these two mechanisms coexist. Kapadia, Westheimer, & Gilbert (2000) proposed that these mechanisms might be located within a single neuron but at different locations in its MRF.

In the present paper we try to explore specific mechanisms of the MRF on a psychophysical level. When looking at the responses of a single cell, it is feasible to come up with accurate representations of its CRF and MRF. Psychophysically, however, the entire system (as opposed to that of a single cell) is available for use by the observer. Thus, drawing a direct parallel with the neuroscience conception of a CRF and MRF is not plausible. If we assume that the visual system would be primarily using a reasonably optimal subset of cells for any given psychophysical task, we can consider the CRF to be roughly the size of the target stimulus being used, while the MRF would be anything outside of the target area that affects the psychophysical task.
The goal of this paper is to gain a better understanding of how the spatial location of stimulation in the MRF affects the target stimulus in the CRF; psychophysically, how the spatial location of a surround masks a central target. More specifically, we wish to examine these effects in terms of collinearity.

It will be necessary at this point to define a simple nomenclature to help distinguish the different spatial locations and orientations of stimuli located in the surrounding area (in general this refers to stimuli in the MRF when referring to single cell recordings in the neuroscience literature or to surrounding masks that lie outside of a central, target stimulus for psychophysical stimuli) of whatever target is being referenced. These targets usually take the form of sinusoidal gratings or lines, both of which intrinsically have an associated orientation. Areas outside of the target in a location extending along the axis of the target’s orientation will be referred to as “end regions” while areas extending orthogonally from the axis of the target’s orientation will be referred to as “side regions.” Additionally, any stimuli in end regions that are of the same orientation as the target will be termed collinear, while all other stimuli of different orientations from the target in the end regions will be termed non-collinear. Stimuli in side regions are always non-collinear (see figure 1 for examples). Using this collinear/non-collinear distinction, there has been evidence for both collinear facilitation and inhibition in the neuroscience literature.
Figure 1. Examples of end regions, side regions, collinearity, and non-collinearity with respect to a central target. (a) Collinear stimulus in end region. (b) Non-collinear stimulus of same orientation as target in side region. (c) Non-collinear stimulus of differing orientation than target in side region. (d) Non-collinear stimulus in end region.

Polat et al. (1998) and Mizobe et al. (2001) used single cell recordings in cats to examine this issue. They found that the response to a target gabor located in the CRF could be increased by placing collinear gabors in the MRF. If the gabors were placed non-collinearly, the firing rate was suppressed. Kapadia, Westheimer, & Gilbert (2000) showed a similar effect in monkeys while using line stimuli instead of gabors.

Li & Li (1994), however, found an inhibitory collinearity effect in single cell recordings. Their experiments, conducted with cat striate cortical cells, showed a greater inhibitory effect of the MRF on neuronal firing to drifting circular grating patterns in the CRF when stimuli in the MRF were collinear.

Results from work done by Knierem & Van Essen (1992) are less clear. They found increased suppression when lines in the MSF matched the orientation of the target lines in the CSF irrespective of the location or the collinearity of lines in the MSF. Similarly, Walker, Ohzawa, & Freeman (1999) had less clear results with respect to
collinearity effects. They used a central grating patch (corresponding to the CSF of a cell) with flankers at eight possible locations around the target. Using these stimuli, they obtained single cell recordings of complex cell firing rates in the visual cortex of cats. They found strong evidence for significantly higher inhibition peaking at one of the eight surrounding spatial locations. Although each cell seemed to have a specific location that increased inhibition, there were individual cell differences in terms of which location produced the increased inhibition. For some cells the maximum inhibitory effect took place in a location collinear to the cell’s preferred orientation, while in other cases it took place in a location orthogonal to the cell’s preferred orientation.

The psychophysical literature has provided just as large a variety of results as the neuroscience literature with respect to collinear effects. Kapadia, Westheimer, & Gilbert (2000) measured observers’ perceived tilt (from vertical) of a single line in the presence of two flanking lines that were tilted either left or right. They found different effects when the flanking lines were collinear versus non-collinear. The collinear setup caused the perception of the target line to be skewed towards the orientation of the flanking lines. The flankers on the side, however, caused the exact opposite effect (although to a much smaller degree) in that the perception of the line was actually skewed opposite that of the orientation of the flankers.

Solomon & Morgan (2000) showed that the addition of collinear flanking gabor around a central target gabor could facilitate a contrast detection task. An interesting additional finding was that adding a full surround of gabor eliminated the facilitation effect even though the non-collinear gabor alone provided no significant increase in detection threshold. Petrov, Verghese, & McKee (2006) recently attributed this and other similar contrast detection facilitation findings to be due primarily to uncertainty reduction, thus putting this type of collinear facilitation in question.

Conversely, the apparent contrast literature has shown both a suppressive collinearity effect and a complete lack of any collinearity effect. Ejima & Takahashi (1985) found a collinearity effect that was phase dependent. When the surrounds were in phase with the target, collinear surrounds led to lower apparent contrast of the target grating when compared to targets in the presence of non-collinear surrounds. When the targets were out of phase, however, Ejima & Takahashi (1985) had results similar to that
of Cannon & Fullenkamp (1991). Neither found a difference in the apparent contrast of sinusoidal grating targets in the presence of collinear versus non-collinear surrounds.

None of this research, however, addresses issues of potential collinearity effects of surrounds on hyperacuity (Westheimer, 1975) discrimination tasks for orientation and spatial frequency. Kapadia, Westheimer, & Gilbert (2000) did utilize perceived orientation of single lines with single line flankers, but they were using orientation differences of five or more degrees, well outside of hyperacuity range.

The purpose of the present research is to begin mapping the effect of different locations of a surround on hyperacuity orientation and spatial frequency discriminations. The idea of collinearity effects will be used as a framework from which to probe the potentially differential strengths of various surround locations.
METHODS

Observers
The observers were five naïve undergraduate students. They all had normal or corrected-to-normal vision and ranged in age from 20 to 22 years. Only one observer participated in both experiments.

Apparatus
Stimuli were presented on 17’ ViewSonic Profession Series PS775 monitors with a mean luminance of 19.2 cd/m^2. Observers were seated 3.32m from the screen in order to obtain a resolution of 120 pixels per degree of visual angle. To achieve the necessary number of luminance levels, video attenuators were used to reroute all gun signals (red, green, and blue) into the green gun (Watson et al., 1986). The displays were linearized using software and linearity was confirmed empirically.

Dell Dimension XPS R450 computers were used to run custom C software with a Genus graphics interface. This was used to create and display stimuli as well as control the experiment.

Observers were seated in a dark room backlit only by a single lamp located behind the plane of the display and shielded from the observer.

Stimuli
Stimuli were “bow-tie” stimuli similar to that used by Cannon & Fullenkamp (1991). These stimuli were made up of two components. The first component was the target to be discriminated, while the second component was an abutting mask. The first component (the target) was a 40-minarc in diameter, sharp-edged (the effect of the surround is lost without a sharp-edge) (Olzak & Laurinen, 2005), circular patch of vertical (or near vertical when orientation judgments are to be made) sinusoidal grating at 4 cycles per degree (or near 4 cycles per degree when spatial frequency judgments are to be made). This target disk was located in the center of the display and had a Michelson contrast of 0.1. The second component was a vertical sinusoidal grating of 4 cycles per degree in the form of a section of an annular ring that abutted and extended an additional
20-minarc from the center disk. The two factors that determined what section of this mask was used were a base axis and a sweep angle (away from the base axis). The surround was then formed by starting at the orientation specified by the base axis (vertical, horizontal, or at a 45 degree diagonal) and expanding in a sweeping arc in both directions for the distance of the sweep angle (0, 15, 30, 60, or 90 degrees). Note that when the sweep angle was 0 degrees there was merely a central disk with no surround, and when the sweep angle was 90 degrees there was a full, annular surround. See Figure 2 for stimuli examples. This surround component was also set to a contrast of 0.1 and was in phase with the target. The display area not covered by the central disk or surrounding mask was set to the mean luminance of the display (contrast of 0).

![Figure 2](image.png)

Figure 2. Examples of stimuli used in the experiments. Note that the central areas represent left tilted targets for the orientation discrimination task, although the actual orientation difference between the centers and the surrounds has been greatly exaggerated for this figure. For spatial frequency discriminations the central target area was a vertical sinusoidal grating of differing spatial frequency from the surround.
**Procedure**

There were two experiments within this study. They were identical in every respect except for the discrimination task. One required observers to make a discrimination between two different orientations for the central disk, and the other required observers to make a discrimination between two different spatial frequencies for the central disk.

Prior to these experiments, observers were trained on hyperacuity orientation or spatial frequency discrimination tasks until they reached a discrimination level corresponding to a $d'$ of approximately 1.2-1.5 (computed using standard signal detection methods with a 6-level rating scale) (Green & Swets, 1966). These training discrimination tasks used the stimuli described above with only the central disk and no surround (sweep angle of 0 degrees). The orientation discrimination task required the observer to discriminate between a counter-clockwise tilted sinusoidal center disk and a clockwise tilted sinusoidal center disk (with the two stimuli being symmetrically tilted around vertical). The spatial frequency discrimination task required the observer to discriminate between a lower frequency sinusoidal center disk and a higher frequency center disk (with the two stimuli varying in spatial frequency symmetrically around 4.0 cycles per degree). Observers were initially given easy discriminations which were continually made more difficult until they reached a stable $d'$ around 1.2 – 1.5. The exact procedures used for this training were identical to the experimental procedures that will be described below. Once these discrimination levels were determined (individually for each observer; they typically were around +/- 0.6 degrees for orientation discrimination and +/- 0.09 cycles per degree for spatial frequency discrimination) they were held constant throughout the experiments as the center (target) disks for the two stimuli in all experimental conditions.

Each experiment consisted of 11 conditions for the 11 possible surround types. The conditions were created by crossing base angle (vertical, horizontal, and diagonal) with sweep angle (0, 15, 30, 60, and 90 degrees). Note that all base angles with a sweep angle of 0 degrees are reduced to only the center target, while all base angles with a sweep angle of 90 degrees have a full annular surround, and this makes 4 of the 15
conditions (3 base angles times 5 sweep angles) redundant leaving 11 unique conditions for each experiment.

Each condition was run in a single sitting and consisted of 80 trials. A set of all 11 unique conditions was called a block. The order that the observer ran the conditions in within each block was randomized. Upon completion of a block, data was analyzed and recorded. A total of 9 blocks were run per observer per experiment.

In each experimental condition there were two possible stimuli (see Figure 3 for an example) with center disks differentiable by either spatial frequency or orientation and set to levels determined by the observer’s pre-experiment training (as previously described). Each of the two stimuli was presented at one of four randomly generated phases (both center and mask component stay in phase by varying together). These were uniquely generated during the loading of the program and thus were a new set of random phases for each new condition. They were each represented equally during the 80 trials (10 of each stimuli/phase combination).

At the beginning of each session, the observer dark adapted under the lighting conditions in the room. The observer then initiated the program which began with a preview mode in which the observer was able to view the two types of stimuli being discriminated in the current condition as many times as desired. When the observer was ready, they exited the preview mode and begin the actual experiment.
Figure 3. Examples of two stimuli in the vertical, 30 degree sweep angle condition for an orientation discrimination task. Orientation differences between the center and surround have been greatly exaggerated for this figure.

Each trial consisted of a randomly chosen stimulus being displayed concurrently with an intermediate frequency tone. The stimulus remained on the screen for 500ms, and the observer was given 5 seconds to respond on a scale of 1 to 6 (for orientation discriminations: 1 = highest surety of being the counter-clockwise tilted target and 6 = highest surety of being the clockwise tilted target; for spatial frequency discriminations: 1 = highest surety of being the low spatial frequency target and 6 = highest surety of being the high spatial frequency target; 2 through 5 were intermediate gradations in both cases). After the observer responded, feedback was given immediately in the form of a tone corresponding to whichever stimulus was actually presented. Trials in which no response was given before the 5 second response window ran out were randomly re-fed into the trial order. When the 80 trials were finished for a given condition, the observer was allowed a break (while remaining in the room to avoid the need to dark adapt again) before beginning the next condition. This continued until they completed all conditions in a block. The observer then began a new block and continued in this manner until all
blocks were completed. Observers ran in the experiment for an hour per day, two to four days a week until they were finished with all blocks.
RESULTS

Experiment 1

The results for the individual observers in the orientation discrimination task (Experiment 1) can be seen in Figure 4. Each graph represents a different observer. Note that the scales along the ordinate axis for each observer may differ due to individual differences in performance. Square symbols represent performance levels in the vertical surround conditions, circular symbols represent performance levels in the diagonal surround conditions, and triangular symbols represent performance in the horizontal surround conditions. Note that at 0 and 90 degrees along the abscissa all three surround locations converge on the same point. This is because at the 0 (control, no surround) and 90 degree (full surround) surround sizes, there is no difference between the vertical, diagonal, and horizontal conditions. The points themselves represent the mean of the d’ values for that condition, and the error bars represent 95% confidence intervals.
Figure 4. Individual observer results for Experiment 1.
The data from all three observers showed similar trends (significance was determined at the 0.05 level by using the overlap of 95% confidence intervals). These trends can be summarized in four main points: (1) all observers showed a drop to near chance performance in the full surround (sweep angle of 90 degrees) condition; (2) no observers showed a significant drop in performance for the horizontal surround conditions (non-collinear surrounds) for any other sweep angle size (15, 30, and 60 degrees); (3) all observers showed an immediate drop in performance for the smallest size (sweep angle of 15 degrees) of the vertical surround condition (collinear surround); (4) all observers showed their highest performance levels in the horizontal surround conditions (non-collinear surrounds), their lowest performance levels in the vertical surround conditions (collinear surrounds), and their performance in the diagonal surround conditions generally fell in between the other two conditions (although it was closer to the vertical condition performance in most cases).

*Experiment 2*

The results for the individual observers in the spatial frequency discrimination task (Experiment 2) can be seen in Figure 5. Each graph represents a different observer. The formatting was the same as that used in Figure 4 for Experiment 1 (see above).
Figure 5. Individual observer results for Experiment 2.
These results were much less clear than those for the orientation discrimination task. Although there was reduced performance when observers went from the control (no surround) to the full surround (90 degree sweep angle), the differences were small and clearly not significant. This failed to replicate previous results (Olzak & Laurinen, 2005). Additionally, there were virtually no significant differences in performance between any of the conditions for any of the observers.

A closer look at the data revealed some potential reasons for concern. Unlike the results for orientation discriminations, adding the full surround in the spatial frequency discrimination task did not cause performance to drop to chance levels. The decrease in performance (when compared to the control condition) was so small that even if there were a real effect, it would be unlikely to be significant with only nine data points for each condition. As the drop in performance from control to full surround should have been the largest change in performance levels between any of the conditions, this would mean that there would likely not be enough power to find significant effects between any of the other conditions (where smaller effects would be expected) as well. However, there is an evident trend in the data in that performance in the horizontal (non-collinear) conditions was always higher than performance in the vertical (collinear) conditions at all surround sizes for all subjects. To account for the possibility that this consistent trend across observers might represent an actual effect that could not be shown statistically due to a lack of power (and to equate performance levels across observers), the data were normalized and combined across observers as can be seen in Figure 6. The normalization was accomplished by converting each observer’s scores onto a scale where 1 represented their control condition (no surround) performance and 0 represented their full surround performance. The nine data points from each condition from each of the three observers were then combined into this new, normalized data set with all twenty-seven data points.
The normalized data for the spatial frequency discrimination task now show the same trends that were found in the individual subjects for the orientation discrimination task with two exceptions: (1) as stated above, performance in the full surround condition did not drop to chance levels; (2) performance in the diagonal surround condition for the 15 degree sweep angle was equivalent to that of the horizontal surround condition for the same sweep angle (rather than between the horizontal and vertical surround conditions as in Experiment 1).
DISCUSSION

Similar to the results of Olzak & Laurinen (2005), we showed that adding a full annular sinusoidal grating surround of similar spatial frequency, orientation, contrast, and phase to a circular target patch of sinusoidal grating causes suppression in orientation (Experiment 1) and spatial frequency (Experiment 2) discrimination tasks. Initially, however, our spatial frequency discrimination results did not show significant suppression until the data were combined across all three observers (after being normalized as defined in the results section). The difference in effect sizes between the orientation and spatial frequency discriminations could point at two different mechanisms as suggested by the work of Olzak & Thomas (1999), although they used overlaid gratings as masks as opposed to surround masks. A simpler explanation could be that it is a single mechanism that responds with different efficacy for different stimulus parameters (i.e., orientation and spatial frequency). Another factor could be that the difference in the effect sizes was due at least partially to individual differences similar to those found by Cannon & Fullenkamp (1993) in studies in which apparent contrast was enhanced and suppressed via annular surround gratings.

Our results provide strong evidence for a collinearity effect in regards to surround modulation for these spatial discrimination tasks. More specifically, our results suggest that the suppressive effect of the surround mentioned above is not merely a function of its size. Instead, location appears to be a major factor as well. Whether or not the surround is located in a collinear region of the surround in relation to the target seems to be of major importance in determining the magnitude of the suppressive effect. Even a small patch of collinear surround caused a noticeable decrease in performance from the control condition; our smallest surround size had a 15 degree sweep angle, which was one-sixth of the full annular surround area, and the effect of this small patch was significant. Meanwhile, even a large patch of the non-collinear surround showed no significant suppressive effect; our largest, non-full surround size had a 60 degree sweep angle, which was two-thirds of the full annular surround area, and the effect of this large patch was not significant. Additionally, by the time the collinear surround size reached a sweep angle of 30 degrees, performance was not significantly different than performance with the full
annular surround. This lends credence to the possibility that most of the suppression caused by the surround is located in a small, collinear section of the surround, and the rest is largely irrelevant.

Our results are in line with some findings in both the neuroscience (Li & Li, 1994) and the psychophysical literature (Ejima & Takahashi, 1985) that show an enhanced suppressive effect for collinear surrounds. While others have shown an enhanced facilitatory effect for collinear surrounds (Kapadia, Westheimer, & Gilbert, 2000; Mizobe et al., 2001; Polat et al., 1998), neither of our experiments utilized a surround that had a facilitatory effect, and thus we could provide no direct support or refutation for findings of an enhanced facilitatory effect for collinear surrounds. However, regardless of the direction of the effect, we did share the same basic result as each of these studies in that the collinear regions of the surround contained the larger share of the overall effect of the surround. Directly confirming this with a facilitatory surround using our hyperacuity discrimination tasks with a lower contrast surround is a possible avenue for future research. Olzak & Laurinen (2005) showed that a lower contrast surround could facilitate this type of discrimination task, although the effects of a full surround seem to be small and highly sensitive to individual differences.

A slightly more complex comparison can be made between our results and those of Solomon & Morgan (2000). The facilitatory effect found by Solomon & Morgan (2000) using collinear gabors was negated when non-collinear gabors (which provided no change in detection threshold on their own) were added to the stimuli. We showed a much different result in that adding non-collinear surround regions to collinear surround regions did not negate the effect of the collinear surrounds. A possible explanation for this is that Solomon and Morgan (2000) used gabor patches, and thus, the center and surround regions were not sharp-edged and abutting. Pilot work done by Olzak & Laurinen (2005) showed that masking effects by a surround in a hyperacuity spatial discrimination task (such as the ones performed in our experiments for this paper) disappear when the surround is not sharp-edged and abutting. Similar results were found in a single cell recording task (Xu, Shen, & Li, 2005). Thus, this discrepancy in effects is possibly due to different mechanisms (one for separated center and surround configurations and one for abutting center and surround configurations).
Our findings differed from the previous findings of Cannon & Fullenkamp (1991) that showed no collinearity effects using the same stimuli types that we used. Although the stimuli were similar, they had their observers perform an apparent contrast task. Apparent contrast and hyperacuity discrimination tasks have been shown to yield differing results in other circumstances (Olzak & Laurinen, 2005). Thus, our findings may not be incompatible with the findings of Cannon & Fullenkamp (1991).

In the neuroscience literature, the discrepancies are harder to resolve. Knierem & Van Essen (1992) and Walker, Ohzawa, & Freeman (1999) failed to find a collinearity effect in their single cell recording studies. They used stimuli that had separated center and surround areas like those used by Solomon & Morgan (2000). There is a possibility that the different mechanism discussed previously is being utilized and causing the lack of an effect, but the discrepancy is not likely to be that simple. This is because previously mentioned work using single cell recordings with the same type of gaps did show an effect (Kapadia, Westheimer, & Gilbert, 2000; Mizobe et al., 2001; Polat et al., 1998). In addition, it is important to recall that these studies were conducted by taking single cell recordings in early visual areas. In contrast, our psychophysical task which gives us no direct knowledge of any individual cell characteristics. It is possible that the collinear effects we found occur at a different processing level, in a different cell type, or that the effects are a result of a more complicated interplay of a large system of cells.
LITERATURE CITED


