Surround modulation of global form perception

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We demonstrate a novel surround modulation of global form perception by using Glass patterns in a center–surround configuration. Glass patterns contain randomly distributed dot pairs, or dipoles, whose orientations are determined by a geometric transform. By integrating across dipoles, an observer can perceive a global structure in the image. We measured the coherence threshold, the minimum proportion of signal dots needed for an observer to detect the global form, at 75% accuracy. The coherence thresholds of the central target Glass patterns were measured either alone or with the presence of various Glass pattern surrounds. Concentric and spiral surrounds increased the coherence threshold for the concentric target compared with that measured for the target alone, while a radial surround had no effect. The coherence threshold for the radial pattern was elevated only by the spiral surround while the spiral and translational targets were not affected by any surrounds. The effect persisted when the center and the surround were segregated by a blank gap and peaked at an optimal gap width. Our results show that global form perception can be modulated by a surround, and this modulation depends on the shapes of the central target and the surround context.

Keywords: Glass patterns, lateral interaction, pattern discrimination, masking

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Introduction

Visual performance to a target can be influenced by the presence of neighboring stimuli (Albright & Stoner, 2002; Schwartz, Hsu, & Dayan, 2007). For instance, the detectability (Chen & Tyler, 2001, 2002, 2008; Petrov, Carandini, & McKee, 2005; Polat & Sagi, 1993, 1994; Yu & Levi, 2000) or apparent contrast (Snowden & Hammett, 1998; Xing & Heeger, 2000; Yu, Klein, & Levi, 2001) of an oriented target can be affected by the presence of flankers. Such lateral interactions depend on several factors such as orientation (Chen & Tyler, 2002; Petrov et al., 2005), contrast (Polat & Sagi, 1994), spatial frequency (Petrov et al., 2005; Yu & Levi, 2000), eccentricity (Petrov et al., 2005; Shani & Sagi, 2005; Xing & Heeger, 2000), and spatial arrangement of the stimuli (Petrov & McKee, 2006; Solomon & Morgan, 2000). In the context of texture segregation (Caputo 1996; Nothdurft, 1991; Wolfson & Landy, 1999), it has been shown that it is easier to segregate a target region from the surround if the line elements constituting the target are at right angles to those of the surround.

Here, we are interested in whether a lateral stimulus can influence the visibility of global forms even when the statistics of local elements are the same. Currently, to the best of our knowledge, there are few studies addressing this issue. Roach, Webb, and McGraw (2008) showed that, after adapting to a circular or a radial periodic pattern, their observers reported a distortion in the perceived orientation of Gabor patches presented in the unadapted regions. It would be difficult to compare this measurement of appearance with the well-established context effects for luminance patterns, which are often studied using threshold measurement. Wilson, Krupa, and Wilkinson (2000) presented a Marroquin pattern, which is produced by superimposing three square grids of dots that are a 60° rotated version of each other, to their observers. Their observers perceived circular shapes that alternately appeared and vanished at different locations. The visibility of the illusory circles seemed to be dependent on a perceived contour in other parts of the display. Such an effect relies on a specific arrangement of image elements. Hence, it would be difficult to use these types of stimuli to study the lateral interactions between different global forms.

We thus used Glass patterns (Glass, 1969) as our stimuli (Figure 1A). A Glass pattern contains randomly distributed dot pairs, or dipoles, whose orientations are determined by certain geometric transforms. Observers with normal visual function can easily perceive the global form of a Glass pattern (Clifford, Holcombe, & Pearson, 2004; Glass & Perez, 1973; Glass & Switkes, 1976; Wilson & Wilkinson, 1998; Wilson, Wilkinson, & Asaad, 1997). It

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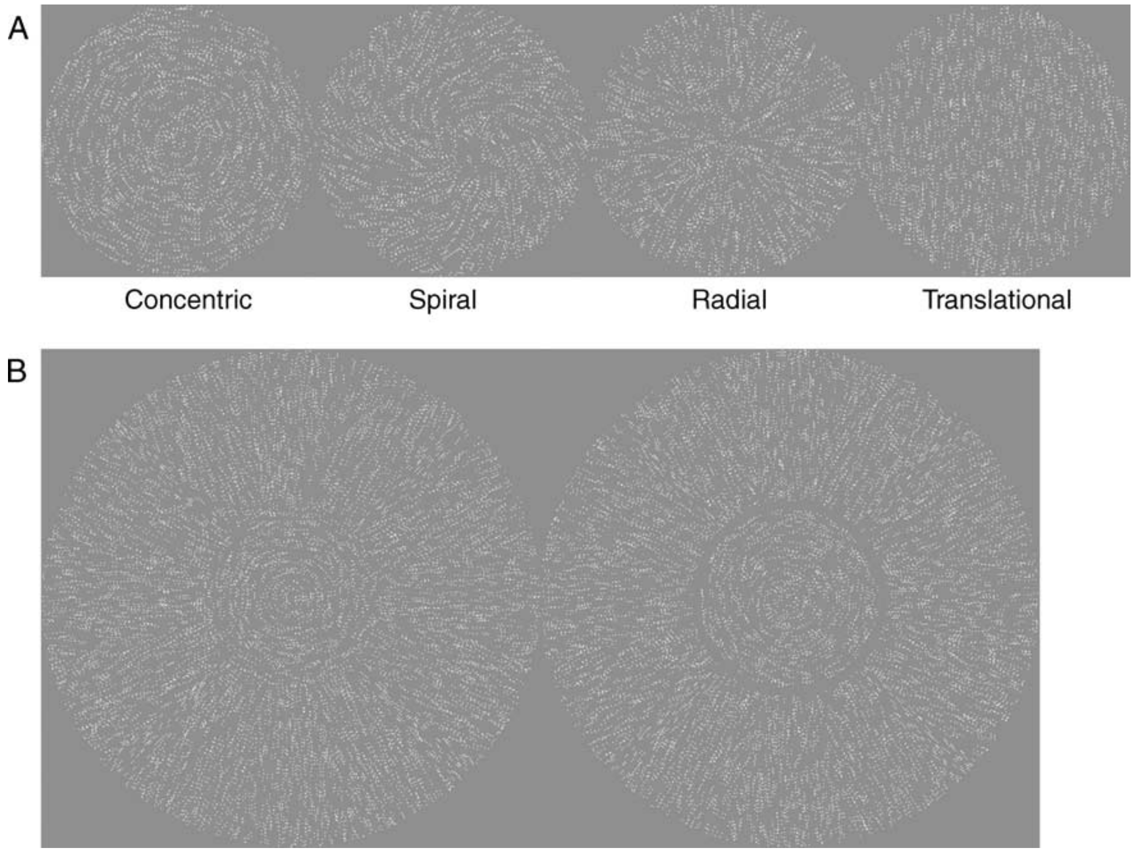

Figure 1. (A) Examples of the four types of Glass patterns used in the experiment. (B) Examples of Glass patterns in center–surround configuration. The threshold of the central target was measured alone or with different types of surround. Here the central target is a concentric pattern and the surround is a radial pattern (left). When a gap is inserted, the surround is moved outward and leaves an empty ring between the center and the surround (right).

is suggested that there are at least two stages involved in the perception of the global form of a Glass pattern: a local stage that uses linear filters to extract information about dipole orientation and a global stage that pools that local orientation information across dipoles to extract the global structure (Chen, 2009; Dakin, 1997; Wilson & Wilkinson, 1998). An advantage of using Glass patterns to tag the response of the global form detector is that the global structure of a Glass pattern can be changed by manipulating the orientation of the dipoles while the overall image statistics, such as Fourier power spectra and the orientation content, remain unchanged (Seu & Ferrera, 2001).

The mechanism underlying detection of the global form in a Glass pattern is tuned to shape. It is more difficult to detect translational and spiral patterns than radial and concentric patterns (Achtman, Hess, & Wang, 2003; Seu & Ferrera, 2001; Wilson & Wilkinson, 1998). It is also easier for a human observer to detect a deviation from a concentric pattern than from a translational pattern (Kurki & Saarinen, 2004). Using the pedestal masking paradigm, it has been found that the detection of a concentric Glass pattern can be impeded by a spiral or another concentric pattern but not by radial or translational patterns (Chen, 2009). Therefore, in addition to allowing us to study the context effect in general, the use of Glass patterns may allow us to explore whether there is a form-specific context effect.

We therefore constructed the Glass pattern stimuli in a center–surround configuration (Figure 1B). The center (target) was a Glass pattern presented in a disk centered on the fixation point while the surround (mask) was another Glass pattern presented in an annulus that is concentric with and adjacent to the target. We measured the coherence threshold for observers to detect the global form, either with the target Glass pattern alone or in the presence of surrounds with different global forms. By configuring the stimuli in this way, we were able to study the effects of the surround on global form perception and whether such modulation was form specific.

Methods

Apparatus

The stimuli were presented on a ViewSonic CRT monitor with a resolution of 1024 (H) × 768 (V) and a frame rate of 75 Hz. The viewing field was 29.7° (H) by 21.5° (V). At a viewing distance of 60 cm, 1 pixel on the screen subtended 0.028° × 0.028°. We used a LightMouse photometer (Tyler & McBride, 1997) to measure the input–output intensity function of the monitor. This information allowed us to compute linear lookup table settings to linearize the output. The maximum luminance of the display was set at 33 cd/m^2. We used Psychtoolbox (Brainard, 1997) for the experimental control and stimulus generation.

Observers

The observers were college students recruited from National Taiwan University campus. There were 8 observers: one was the author while the others were naive to the purpose of this study. All the observers had normal (20/20) or corrected-to-normal vision.

Stimuli

We used Glass patterns (Figure 1A) composed of white dot pairs (33 cd/m^2) on a dark-gray background (9 cd/m^2). Each dot was a 0.028° × 0.028° square. The dot density was 4%, and the intra-dipole dot distance was 0.183°. The structure of a Glass pattern can be described by a logarithmic spiral, which has the parametric equation in polar space $r = ae^{b\theta}$, where r and θ are the radius and the angle defining the polar space, a is a scale factor, and b determines the curvature of the spiral. The logarithmic spiral has a property such that the angle between the tangent line and the radial line at any point on the spiral is constant. In a Glass pattern, the tangent line defines the orientation of a dipole. Thus, the angle between the dipole and the radius of the stimulus aperture is called the spiral angle (Dickinson & Badcock, 2007; Prazdny, 1984; Seu & Ferrera, 2001) or spiral pitch angle (Webb, Roach, & Peirce, 2008) and is used to describe the form in Glass patterns. The concentric and radial patterns were special cases that had spiral angles of 90° and 0°, respectively. Dipoles in translational patterns were created by shifting one dot of a dipole in either a vertical or horizontal direction.

A Glass pattern contained signal dipoles and noise dipoles. The signal dipoles were those whose orientation followed the pre-designated geometric transforms, and the noise dipoles were those with random orientation. The visibility of a Glass pattern was measured by coherence, which was defined as the number of signal dipoles divided by the number of total dipoles. All Glass patterns were generated online and refreshed for each trial.

In the no-gap condition, the target was a Glass pattern presented in a circular aperture (2.5° radius) centered on the fixation point (Figure 1B, left). The surround was another Glass pattern presented in an annulus that was concentric with the target and adjacent to the target region. The surround ring had an inner radius of 2.5° and an outer radius of 8°, and thus was 5.5° in width. There were three types of Glass pattern for both the center and the surround: concentric, radial, and spiral (45° spiral angle), creating nine (3 × 3) different center–surround combinations. There was also one center-alone condition for each type of Glass pattern. In addition, we measured the threshold of vertical (translational) Glass patterns under center-alone, vertical-surround, and horizontal-surround conditions. In the gap conditions, the stimuli were essentially the same as in the no-gap condition except that a blank ring of varying width (from 0.2° to 0.6°) was inserted between the target and the surround (Figure 1B, right). In these cases, the surround was simply moved outward, leaving an empty ring between the center and surround. The width of the surround was retained.

Procedure

We measured the coherence threshold, or the minimum number of signal dipoles necessary for observers to detect the global form of the target, with a temporal 2AFC paradigm. In each interval, a fixation point flashed for 80 ms, and then the stimulus was presented for 135 ms. The two intervals were separated by a 450-ms blank period, in which only a fixation point on a gray background was shown. The thresholds of the target were measured with or without the presence of various types of Glass pattern surrounds. The surrounding patterns were the same in both intervals: a target Glass pattern was randomly presented in either of the two intervals, and a noise pattern (zero coherence) was presented in the other. The purpose of the noise pattern was to balance image statistics in the two intervals. The coherence of the surround Glass patterns was always 100%. The task of the observers was to indicate which of the two intervals contained the target stimulus by pressing one of two keys on a keyboard. A PSI adaptive threshold-seeking algorithm (Kontsevich & Tyler, 1999) was used to measure the coherence threshold at 75% correct response level. One threshold measurement contained 40 trials. Each data point represented the average of at least four measurements.

Results

Figure 2 shows the coherence thresholds averaged over five observers in different target–surround combinations. We ran paired t-tests to compare the coherence threshold in different surround conditions to the center-alone condition. The concentric surround ($t(4) = 11.06$, $p <$

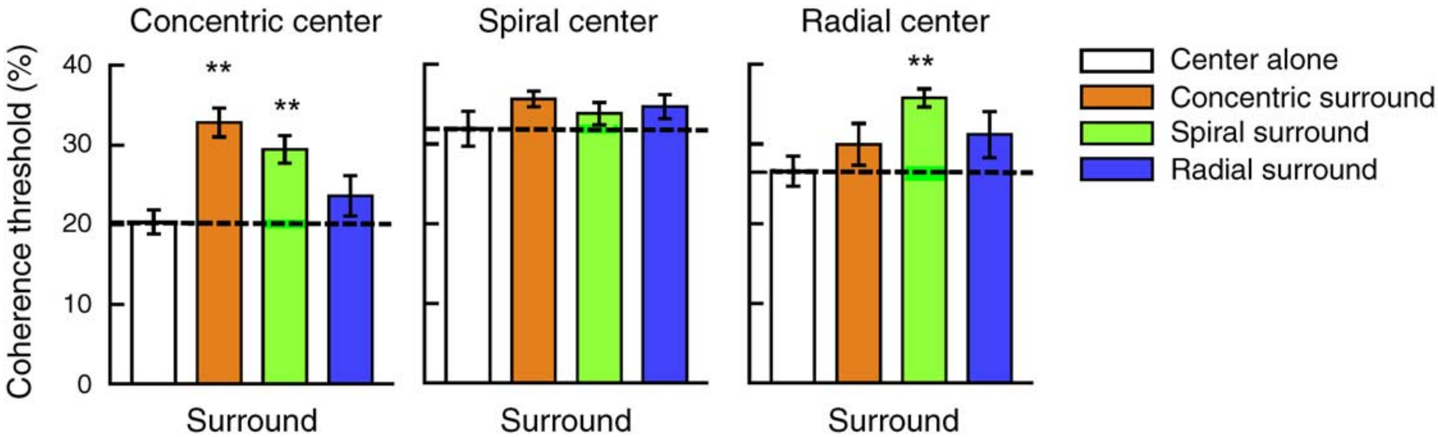

Figure 2. Experimental results averaged over five observers. Effect of surround form on the coherence threshold of the central target. The "**" above represents significant difference in coherence threshold compared to the center-alone condition ($p < 0.01$). The dash line indicates no surround modulation. The error bar is one standard error of mean.

0.01) and the spiral surround ($t(4) = 5.11$, $p < 0.01$) elevated the coherence threshold of the concentric target from 20.3% to 32.8% and 29.4%, respectively, and the radial surround had no effect on a concentric target. The coherence threshold of the radial pattern was elevated only by the spiral surround (from 26.5% to 36.7%, $t(4) = 7.04$, $p < 0.01$). The spiral Glass patterns were not affected by any type of surround.

We also tested translational (vertical) targets with vertical and horizontal surrounds. By using translational stimuli, we investigated whether there is a surround effect for Glass patterns when the center and the surround have cohesive oriented elements instead of complex structures. Figure 3 shows the results for the translational (vertical) target. The threshold was similar under center-alone, vertical-surround, and horizontal-surround conditions.

In the center-alone condition, the concentric pattern had the lowest threshold (20.3% coherence), and the spiral (31.9% coherence) and translational (36.6% coherence) patterns had the highest thresholds. This is consistent with previous literature (Achtman et al., 2003; Seu & Ferrera, 2001; Wilson & Wilkinson, 1998).

The above result was from the no-gap condition. The surround was immediately adjacent to the center region. Therefore, it might be argued that the surround suppression result was due to an increase of target location uncertainty when the observers were unable to localize the boundary of the target. This uncertainty may lead observers to confuse the surround with the target pattern, which may have elevated the threshold. We tested this hypothesis by inserting a blank gap between the center and the surround (see Methods section for details). This gap provided a cue for figure–surround segregation and reduced the location uncertainty.

Seven observers participated in the experiment in which a 0.2° gap was inserted. The pattern (Figure 4) was generally consistent with the previous result: the concentric ($t(6) = 5.78$, $p < 0.01$) and spiral surrounds ($t(6) = 4.15$, $p < 0.01$) increased the coherence threshold for the concentric target, and the threshold of the radial target was elevated by the spiral surround ($t(6) = 9.57$, $p < 0.01$). No other surround effect was observed. To further investigate the relationship between the surround suppression and the distance between the center and the surround, we used the concentric pattern as the central target and varied the width of the gap from 0.2° to 0.6°. The results for three observers are shown in Figure 5: the width of the gap is plotted against the normalized threshold, in which the threshold of the surround condition is divided by the threshold of the center-alone condition. The coherence threshold was not affected by the radial surround at any gap width. In the concentric surround and the spiral surround conditions, the suppression effect first increased and then decreased as

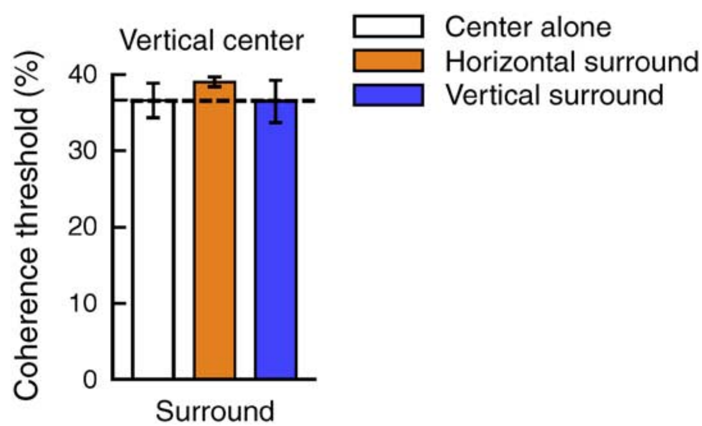

Figure 3. Experimental results averaged over five observers. Effect of vertical and horizontal surrounds on the coherence threshold of the vertical central target. The "**" above represents significant difference in coherence threshold compared to the center-alone condition ($p < 0.01$). The dash line indicates no surround modulation. The error bar is one standard error of mean.

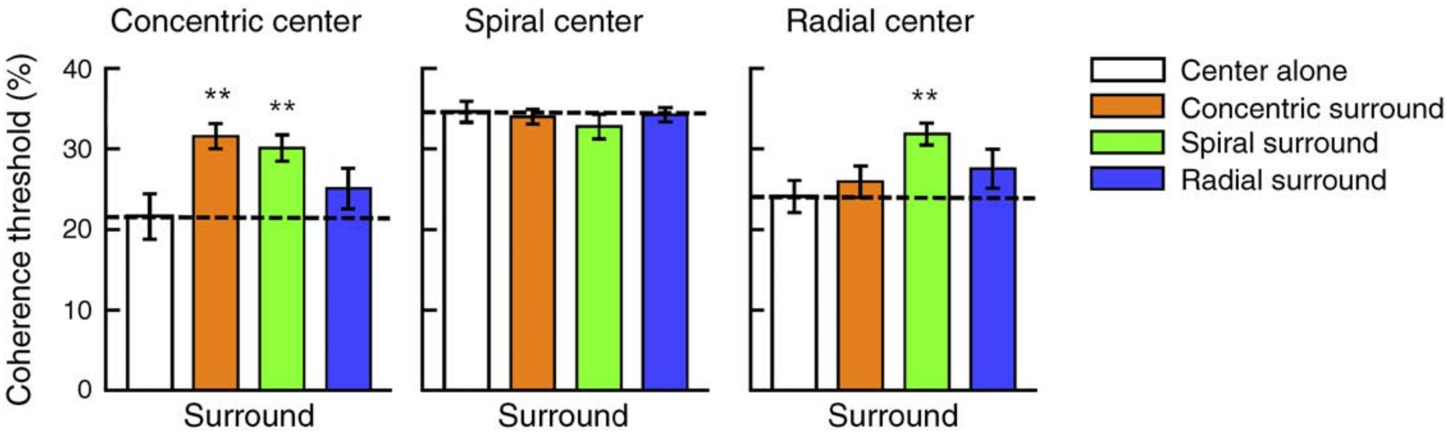

Figure 4. Experimental results averaged over seven observers. Effect of the blank gap (0.2° in width) between the center and the surround. The results are similar to Figure 2. The "**" above represents significant difference in coherence threshold compared to the center-alone condition ($p < 0.01$). The dash line indicates no surround modulation. The error bar is one standard error of mean.

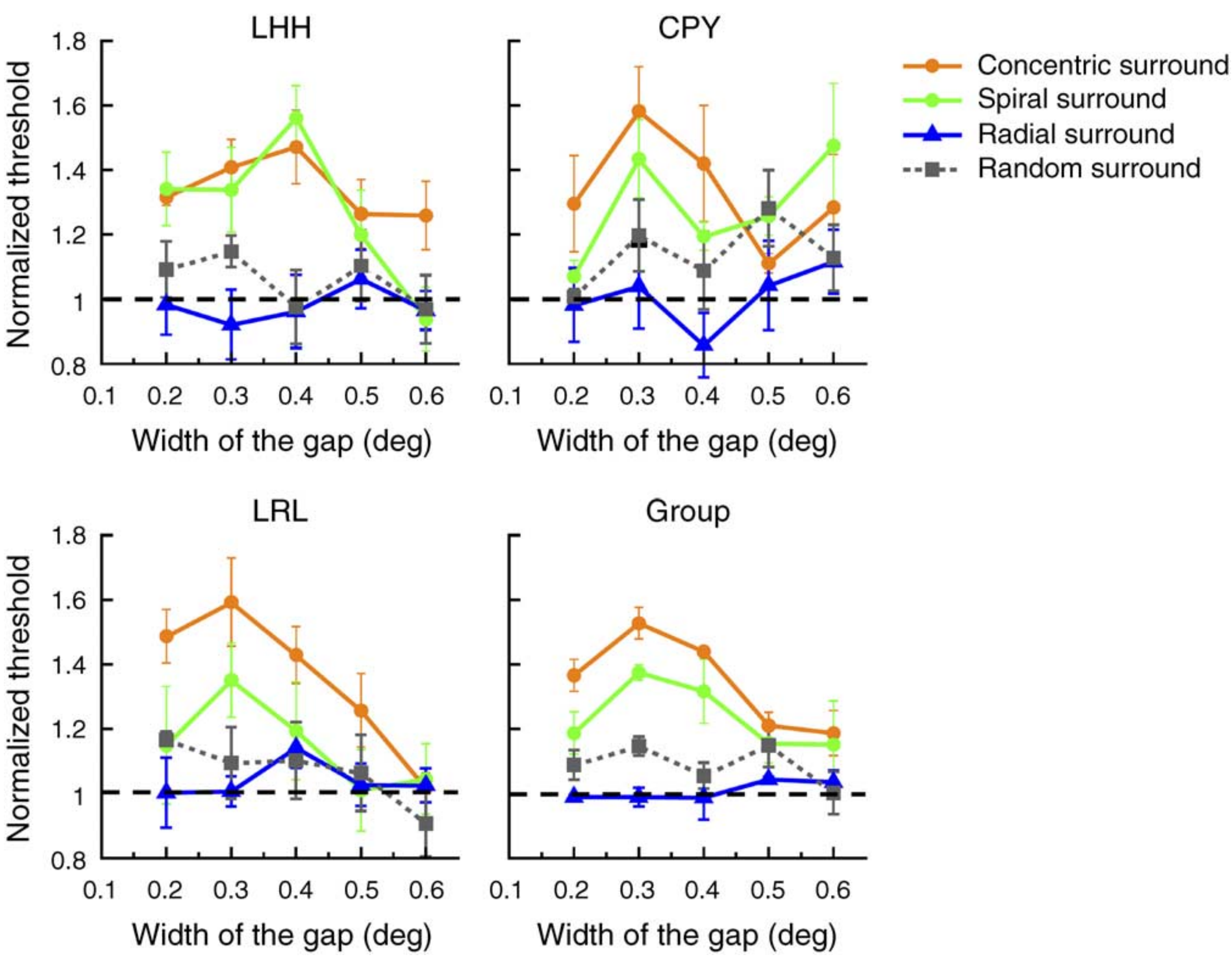

Figure 5. The effect of the width of the gap on the surround modulation. The individual data and the group data are plotted. For the concentric and spiral surrounds, the amplitude of suppression first increased and then decreased as the gap was widened. The random surround produced weak threshold elevation while the radial surround had no effect. The horizontal dash line indicates no surround modulation. In the individual data, the error bar is one standard error of mean over measurements, and in the group data, the error is one standard error of mean over three observers.

the gap was widened and diminished when the width of the gap was greater than 0.5° (Figure 5). The peak suppression occurred at a gap width of around 0.3° for two of three observers and at a gap width of 0.4° for one observer. Thus, surround suppression is tuned to distance. In order to compare with the structured surround, we also included conditions with a random surround, in which the surround pattern was constructed of randomly orientated dipoles (gray squares and lines in Figure 5). The purpose of this condition was to test whether there is a general surround effect that is not specific to forms. The effect of the random surround was very weak, especially compared with that of the concentric and spiral surrounds. It also showed no clear tuning to gap width. Thus, there was little, if any, non-form-specific lateral effect in our data.

Discussion

We used Glass patterns to demonstrate the surround modulations of global form perception. We found that the presence of Glass patterns in the surround could elevate the detection threshold of the central Glass patterns. This surround modulation effect was tuned to shape. Concentric targets were suppressed by concentric and spiral surrounds while radial targets were suppressed by spiral surrounds. No surround modulations were found for spiral or translational targets.

Comparison with other contextual modulation effects

Studies of orientation discrimination of single bars (Caputo, 1996; Wolfson & Landy, 1999) and texture segmentation of line elements (Nothdurft, 1991; Wolfson & Landy, 1995) have shown that the influence of background on the target depends on the orientation contrast between them. However, we found that the coherence thresholds of translational (vertical) Glass patterns were the same under the center-alone, the vertical-surround, and the horizontal-surround conditions. This result is not consistent with the pop-out effect of orientation contrast, which predicts that the vertical center would be easier to detect in the horizontal-surround condition than in the vertical-surround condition. Moreover, our result shows that the detection of spiral patterns was not affected by any type of surround, and the thresholds of the radial pattern were similar under concentric and radial surrounds. Thus, the surround modulation of Glass patterns with complex forms cannot be explained by interactions between local orientation filters at the boundary of the center and the surround.

Habak, Wilkinson, Zakher, and Wilson (2004) also demonstrated a form-specific lateral interaction. They used radial frequency patterns whose radius changed periodically about a circle. They showed that it was harder for their observers to discriminate the curvature of a radial frequency pattern when a surround radial frequency pattern was presented. Furthermore, this masking effect was greatest when the curvature extrema of the mask were aligned with those of the target. Such curvature-specific masking cannot be explained by the properties of local orientation filters.

Solomon, Sperling, and Chubb (1993) showed that the apparent contrast of a center consisting of random bright and dark regions depends on the contrast of another random surround. This contrast induction effect on unstructured patterns may suggest that the mere presence of a surround can affect visual performance to the target. That is, there may be a general surround effect that is produced by the change of contrast in the surround and is not form specific. However, as shown in Figure 5, the random surround produced little, if any, effect on concentric target detection. Thus, even if there were a contrast-based lateral effect, it played a minor role in the surround modulation we found.

Our results were different from the crowding effect (for a review, see Levi, 2008). Crowding refers to the way in which the presence of other objects nearby can impair discrimination and recognition of an object. Crowding is absent, or rather weak, at the fovea (Levi, Klein, & Hariharan, 2002; Strasburger, Harvey, & Rentschler, 1991). Our target was presented in a circular aperture of 2.5° centered at the fixation, where the crowding effect is minimal. In addition, the crowding effect follows the rule of similarity (Felisberti, Solomon, & Morgan, 2005; Kooi, Toet, Tripathy, & Levi, 1994), that is, the crowding effect is reduced when the target and flankers have different visual properties. Thus, the crowding effect would predict threshold elevation to be greatest when the center and the surround were the same. This is inconsistent with our results, in which there was no threshold elevation when both the center and the surround were radial, spiral, or translational patterns.

Roach et al. (2008) reported that adaptation to global form gratings in the surround can bias perception of the orientation of a subsequently presented Gabor patch located in the center. Compared with their result, our data show that the global form of the surround interferes with perception of the central target when the center and the surround are presented simultaneously. Because Roach et al. used a local Gabor patch as the test stimulus following the adaptation phase, they explained the aftereffect as feedback from the global form detectors to local orientation filters. In contrast, we demonstrate interactions between global form detectors by using globally defined forms in both the center and the surround. Our result is consistent with the study by Wilson et al. (2000), who showed that the visibility of a circular form in a Marroquin pattern is suppressed by highlighting another circular form at a remote location.

Shape tuning

The curvature of the global form appears to play an important role in surround modulation, as only a curved surround (such as the spiral or concentric surrounds) can suppress the detection of the concentric target, and only a spiral surround can suppress the detection of the radial target. In addition, we did not find the radial or translational surround effects on any targets. This shape tuning result is similar to our previous data from pedestal masking, in which the target and the mask were superimposed Glass patterns (Chen, 2009). In that study, a concentric target was masked by concentric and spiral pedestals, while a radial target was masked only by a spiral pedestal.

However, Webb et al. (2008) did not report that spiral masks had a greater effect on a radial target. Webb et al. used texture patterns constructed from randomly distributed Gabors to create a percept of a global form. Their stimuli were similar to our Glass patterns but had Gabor patches in place of dot dipoles. They measured the threshold elevation for detecting global forms in various spiral angles followed by a backward mask with the same or different spiral angles. They found that the amount of threshold elevation depended on the difference in spiral angles between the target and the backward mask. They showed that a radial mask had the strongest masking effect on a radial target, while a spiral mask at 45° had little masking effect. This discrepancy may result from the difference in stimuli. It is possible that the orientation filters are more sensitive to the stimulus presented by the Gabor array. Thus, their results may not only reflect the properties of global form detectors but also the masking effect in the orientation filters at an earlier stage.

Comparison with pedestal masking effect

In the discussion so far, we have excluded the possibility that our surround masking effect is due to the interaction between local orientations, the modulation of surround contrast, and the crowding effect. The strong shape tuning suggests that this effect occurs after the analysis of shape information. In the following discussion, we investigate whether the current effect can be accounted for by pedestal masking, which has been used by some researchers to explain surround modulation (Snowden & Hammett, 1998, Solomon & Morgan, 2000).

The shape tuning of the surround modulation is similar to that of pedestal masking. Chen (2009) showed that the masking effect of both concentric and spiral masks on a concentric target was greater than the effect of a noise mask. Hence, some might suggest that the surround modulation effect is just an extension of pedestal masking, that is, that the surround actually falls within the receptive field of the form detector for the central target and produces an effect in the target detector just as a pedestal does. However, while this explanation may account for the surround suppression and shape tuning, it cannot explain the gap width effect we also observed (Figure 5). If the surround modulation were due to the overlap between the surround and the receptive field of the target detector, the amplitude of the modulation should simply depend on the size of the overlapping area. As the gap width increases, the surround is pushed outward. Hence, this overlapping area, and in turn the input from the surround to the target mechanism, should decrease with gap width. That is, compared with the no-gap condition, the surround should have the same effect as a weaker pedestal when the gap is inserted. Since the pedestal masking effect increases monotonically with pedestal strength (Chen, 2009), the modulation should simply decrease with the increase of gap width. However, for all our observers, the detection threshold first increased and then decreased with gap width. The amplitude of the modulation did not decrease monotonically with gap width but peaked at an optimal distance between the center and the surround.

Furthermore, to explain our lateral masking result in terms of pedestal effect, the detector for the central Glass pattern should have a receptive field that extends to the surround region. In the literature, the psychophysical equivalence of the receptive field is normally measured with a spatial summation experiment. Wilson and Wilkinson (1998) showed that the coherence threshold of a small Glass pattern decreased as the size of the Glass pattern increased. However, this spatial summation effect diminished when the radius of the Glass pattern was greater than 2.5°. Hence, one can conclude that the receptive field of the Glass pattern detector should have a radius of about 2.5°. We deliberately set the size of our stimulus at a 2.5° radius to avoid possible contamination from the pedestal effect.

Of course, given the similarity in global form selectivity, one may ask whether the pedestal effect reported earlier (Chen, 2009) could be contaminated by surround modulation. Current data cannot resolve this possibility. It is possible that the pedestal effect and the target effect simply have similar shape tuning, just as orientated pattern detection and lateral masking have a similar orientation tuning (Chen & Tyler, 2002). To clarify this issue, one may need to investigate pedestal masking of global form using a smaller stimulus.

Conclusion

The aim of the present study is to demonstrate the surround modulation of global form perception. We used Glass patterns in center–surround configuration to measure the influence of a surrounding form on the central form. We found that the detection threshold of a concentric pattern was elevated by concentric and spiral patterns, and the threshold of a radial pattern was elevated by a spiral pattern. No surround modulation was found for spiral or translational targets. By inserting a blank gap between the center and the surround, we showed that the modulation cannot be explained by pedestal masking or the uncertainty of target location induced by the presence of the surround. The surround modulation reflects the interactions between global form detectors with no overlapping receptive field. It cannot be explained by pedestal masking, local orientation contrast, surround contrast modulation, or the crowding effect. It is a property of the global form detectors.

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