Crowding is directed to the fovea and preserves only feature contrast

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The abundant literature on crowding offers fairly simple explanations for the phenomenon, such as position uncertainty or feature pooling, but convincing evidence to support these explanations is lacking. In part, this is because the stimuli used for crowding studies are usually letters or other complex shapes, which makes it hard to determine exactly what kind of information is lost. In our experiment, we asked observers to identify simultaneously the slants (left or right) of three horizontally aligned Gabor targets. The targets were presented at 6° in the periphery, and their size and separation were chosen to incur strong crowding. The loss of information about the position or orientation of individual members of the Gabor triads does not explain our results. Instead, crowding appears to be a particular form of collective information loss. Firstly, the outmost target was crowded much less than the other targets, which rules out explanations based on simple pooling and shows that crowding has a pronounced foveal directionality. Secondly, the specific pattern of confusion shown by all the observers indicates that the only reliable information available to them was orientation contrast, that is, the number (and, to a lesser degree, the location) of sites where slant changed. Thus, crowding appears to spare only the most salient peripheral information, which supports the hypothesis that crowding is caused by limitations of attentional resolution.

Keywords: crowding, information processing, anisotropy


Introduction

Crowding is, arguably, the most distinctive feature of peripheral vision. Although it is most commonly discussed within the context of reading and visual disorders, for example, amblyopia, crowding is a universal phenomenon and has implications for such diverse tasks as object recognition, visual search, and saccadic eye movements.

Crowding has been studied since the early 1960s (Stuart & Burian, 1962), but its physiological basis is still not understood. One of the earliest explanations of crowding was suggested by Estes (1972, 1974). Using the observation that confusable (similar) letters produce stronger crowding, Estes suggested that crowding happens because similar features of nearby letters inhibit each other. More recently, Chung, Levi, and Legge (2001) argued along the same lines referring to similarities between visual masking and crowding. An alternative explanation of crowding was originally proposed by Wolford (1975) and later incorporated into the Krumhansl and Thomas (1977) model. They argued that because peripheral features tend to be mislocalized (toward the fovea), these features are mixed with those on the foveal side, which produces crowding. A conceptually similar “pooling” hypothesis was later introduced by Levi, Hariharan, and Klein (2002), Parkes, Lund, Angelucci, Solomon, and Morgan (2001), and Pelli, Palomares, and Majaj (2004). They suggested that once individual features are detected, the feature information is pooled over a local area of visual field, causing crowding.

The local inhibition explanation predicts that the feature signal is strongly reduced or even completely lost. The pooling explanations are less specific about what happens to the signal. The common assumption is that the location of individual features is lost. In other words, when experiencing crowding, we retain the “what” part of the signal, but not the “where” part.

Although these crowding hypotheses make specific predictions, there have been few direct tests of their validity. Perhaps, this is in part explained by the particular stimuli traditionally used in crowding studies. Crowding was first observed in reading (Ehlers, 1936) and in clinical tests of visual acuity (Ehlers, 1953) where letters or letter-like characters were a natural choice. Despite their practical significance, letters are poor candidates as visual stimuli for crowding. Because it is not well understood how such complex shapes are processed and encoded, it makes it hard to analyze what happens in crowding. Indeed, in one of his most cited papers, Bouma (1970) suggests using less complicated stimuli.

The aim of this study was to determine explicitly what kind of information is lost in crowding. We asked observers to identify the orientations of a triplet of horizontally aligned Gabor patches each slanted left or right in all
possible combinations. By using the simple stimuli in which the orientation and spatial frequency of all components were well controlled, we were able to analyze precisely what features were confused in crowding and the way in which they were confused. Simplified stimuli in the form of bars, circular patches of grating, Gabors patches, or letters made of Gabors have been used in several recent crowding studies (He, Cavanagh, & Intriligator, 1996; Levi et al., 2002; Parkes et al., 2001; Wilkinson, Wilson, & Ellemberg, 1997). Stimuli in the present study were modeled from those used by He et al. (1996).

A study by Parkes et al. (2001) concluded that information about individual target orientations was averaged in crowded stimuli. However, it is possible that the averaging found in this study was due to the particular task used rather than to crowding. In their orientation discrimination experiment, the number of targets was varied and the target positions were randomized, which made subjects uncertain about the locations of the targets. In this case, averaging becomes the best strategy, especially when the targets are more numerous than the distractors as was true for half the conditions in their study. The same experiment repeated in the fovea also indicated strong averaging, but it is thought that there is no crowding in the fovea.

An experiment with a single target and a variable number of distractors would be more informative because there would be no strong incentive for a subject to pool target and distractor signals. Such an experiment was carried out by Felisberti, Solomon, and Morgan (2005). One of the two tested subjects showed no significant change in orientation discrimination performance, when the number of distractors varied from 2 to 5. The second subject showed some effect, but only when the target position was cued, and there was no significant effect for the noncued target. Also, there was no significant change in subjects’ ability to detect an odd-orientation target among the array of distractors, when the number of distractors changed from 4 to 15. Altogether, the above evidence strongly suggests that averaging can be chosen by subjects as a strategy when the target location is uncertain.

Another potential problem with both the Felisberti et al. (2005) and Parkes et al. (2001) studies is that target and distractors in these studies often had similar orientations, which induced a strong illusory tilt (Solomon, Felisberti, & Morgan, 2004) and a related increased orientation discrimination thresholds. Because these effects persist in the fovea, they are not related to crowding (Solomon & Morgan, 2006) and are possibly confounding crowding in the above studies.

Here, we report that no trivial loss of positional information resulting from averaging can explain crowding. Also, it cannot be explained by inhibitory lateral interactions, similar to surround suppression. We show, instead, that crowding strongly depends on the dissimilarity of neighboring visual elements as well as on their order (inward–outward). We argue that the results can be parsimoniously explained if all information except for the local feature contrast calculated in an anisotropic fashion is lost in crowding.

## Methods

### Apparatus

Stimuli were displayed on a gray, 42-cd/m² background and viewed through Wheatstone stereoscope on a pair of linearized 17-in. Sony Trinitron G220 monitors. The stereoscope was previously used to study stereoscopic properties of crowding. However, for this study, it was merely used for convenience; all components of the binocular stimuli were presented at zero disparity. The display was 1,400 × 1,050 pixels; viewing distance was 65 cm. A pixel subtended 1.2 arcmin.

### Subjects

Four experienced psychophysical observers with normal or corrected-to-normal visual acuity were tested. Observers were trained for a short time (10–15 min) to get acquainted with the stimuli and the task and to collect pilot data to estimate the individual performance level.

### Stimuli

The test target was a horizontal triplet of standard cosine-phase Gabors (σ = λ/√2) in which ~1.5 periods (1°) of the sinusoidal pattern were visible, as shown in the top panel of Figure 1. Separation between neighboring Gabors was 4L. Pilot experiments were used to estimate the stimulus size, which would give approximately 50% responses correct. The resulting Gabor spatial frequency was chosen to be 6 cpd for all four observers. The Gabor contrast was fixed at 90%. The Gabors were slanted ±45° from the vertical. Given the two choices of slant for each of the three Gabors, eight triplets shown in the bottom panel of Figure 1 span all possible combinations. Each of the triplets was used as a target with equal probability.

### Psychometric procedure

The fixation pattern, consisting of two low-contrast concentric circles, was displayed at the center of the screen and remained continuously visible throughout fixation and target presentation. We used an eight-alternative forced-choice procedure. The test triplet determined by a random preshuffle of the eight possible triplets appeared to the left of fixation at 6° eccentricity for 150 ms. Next, the eight response triplets were presented at the same eccentricity.
as the test triplet but to the right of fixation as shown in Figure 1, always in the same order. The mouse pointer appeared at a random location among the triplets. Subjects were free to move their gaze toward the response triplets and had unlimited time to make their choice. The task was to click the mouse pointer on the triplet matching the test triplet. As a control, one subject ran the experiment with the whole stimulus mirror-reversed: The targets were shown on the right, whereas the responses (also mirror-reversed) were shown on the left. Experimental data have been accumulated in five trial blocks, with 160 trials per block (i.e., 100 trials per triplet) for each observer.

Results

The raw experimental data are shown in Figure 2a in the form of confusion matrices. Data for individual observers are shown in the first four columns, and data averaged over the four observers are shown in the last column. There was no significant difference between P.V.’s data, which were collected for the stimulus with reversed laterality, and the rest of the observers. The scaled-up copy of the averaged confusion matrix is shown below the individual data. The eight triplet configurations (shown pictorially) label its rows and columns. Note that the configurations are arranged by the orientation of the outward element (in the top four triplets, the first Gabor is tilted left; in the bottom four, the first is tilted right), which differs from the order in which the choices were presented in the experiment (see lower part of Figure 1). The shaded boxes with numbers show the percentage of trials on which the observer identified the row triplet (target) with one of the column triplets (response). Thus, the diagonal elements give the percentage of correct identifications. Darker shades indicate higher percentage.

We first observe that the shaded squares are almost absent in Quadrants I and III of the confusion matrix (as marked in Figure 2a). This means that triplets where the outward element was slanted to the left were almost never confused with triplets where the outward element was slanted to the right and vice versa. Thus, the orientation of the outward Gabor could be easily identified by all observers.

This result is more explicit in Figure 2b, where all the errors (off-diagonal elements of the confusion matrix) are binned into four categories: outward Gabor orientation (#1), middle Gabor orientation (#2), inward Gabor orientation (#3), and orientation total (or.). The last is the total of the three orientations, where the order of the slants is immaterial. For example, both \( \backslash / \) and \( \backslash / \) triplets are “two slanted left, one slanted right,” and confusing the two does not count as an error in this category. Generally, confusing triplets, which can be obtained from one another by a permutation of their elements, did not count as an or. error. The percentage contribution of each error category to the error total is plotted along the y-axis.

Note that a particular element of the confusion matrix can contribute to several categories of errors. Thus, the \( \backslash / \rightarrow \backslash / \) confusion element contributes to both #2 and #3 categories of errors, whereas the \( \backslash / \rightarrow \backslash / \) element contributes to #2 and or. categories. This also means that bars in Figure 2b add up to more than 100% because each bar represents an independent percentage of the total number of errors.

Error bars (1 SD) were calculated assuming binomial distribution for the total number of counts in each confusion matrix element; error bars for the average data did not include variation among the subjects.

For all subjects, performance for the middle element was the worst. The outward Gabor was the least affected by crowding and accounted for mere 10% of the errors. When subjects made a mistake, they were, effectively, at random about the triplet orientation total (or. category); for example, they were unable to discriminate between “two slanted left, one right” and “two slanted right, one left.” The chance performance level for this category of errors is indicated by a small arrow on the right-hand side in Figure 2b.

![Figure 1](image-url)
Because there were almost no data in Quadrants I and III of the averaged confusion matrix and because data in the remaining two quadrants were fairly symmetrical with respect to swapping left and right slants of the triplet elements (which indicates no major left–right bias in the data), the remaining two quadrants were averaged over the left–right swapped matrix elements (e.g., the /\ \rightarrow /\ element was averaged with the /\ \rightarrow /\ element). In this way, the full confusion matrix was reduced to the 4 × 4 matrix shown in Figure 2a. The purpose was to get a better signal-to-noise ratio and to make the following confusion patterns more explicit:

(i) The uniformly slanted triplet /\ (or /\) was almost never confused with other triplets (<4%) and vice versa.

(ii) The largest confusion was between the /\ and /\ triplets, and the /\ \rightarrow /\ confusion was significantly more common than that in the opposite direction (38% ± 3% vs. 16% ± 2%). The asymmetry can be seen for three of the four observers.

(iii) The /\ triplet was equally confused with the /\ and /\ triplets (12% ± 2% and 13% ± 2%), whereas the opposite confusion pattern (e.g., /\ \rightarrow /\) was significantly less frequent (8% ± 1% and 5% ± 1%).

Note that the averaging obscured one residual difference, which showed up for all four observers: The percentage of correct identifications for the /\ triplet was significantly lower than that for its mirror image, /\ (54% ± 3% vs. 72% ± 4%). Apparently, this asymmetry reflects some interac-
tion between the slant of the triplet Gabor and the side on which the target was presented, but the character of this interaction is not clear.

**Discussion**

The main results can be summarized as follows:

I. Crowding among Gabor patches was characterized by strong inward–outward anisotropy, to the effect that the outward element was crowded much less than the inward elements.

II. The orientation total (or.) of triplet elements could not be identified with any degree of certainty.

III. Confusion Patterns i, ii, and iii above indicate that crowding depends on neighboring triplet components, as well as on their order within the triplet.

One might notice that the most common errors, that is, $\backslash\slash$ and $\backslash\small{|}/\small{|}\backslash$, involve mirror-symmetric triplets. Is it possible to explain our data by assuming that we are just prone to confuse mirror symmetric images? Not quite. This mechanism does not explain why the $\backslash\slash \rightarrow \backslash\small{|}/\small{|}\backslash$, confusion pattern was much more frequent than its mirror-symmetric counterpart, $\backslash\small{|}/\small{|}\backslash \rightarrow \backslash\slash$. It also predicts that $\backslash\small{|}/\small{|}\backslash \rightarrow \mslash\mslash\mslash\mslash$ confusions would be common (as well as $\mslash\mslash\mslash\mslash \rightarrow \backslash\small{|}/\small{|}\backslash$), which blatantly contradicts the data.

**Inward–outward anisotropy of crowding**

The inward–outward anisotropy found here replicates the results from our preceding paper (Petrov, Popple, & McKee, in press), in which stimuli shown in Figure 3 were used to compare crowding and surround suppression. When fixating at the dot, the slant of the target Gabor is much more apparent with the mask on the inside than on the outside.

The anisotropy for letter stimuli was first noticed by Shaw (1969) and Bouma (1970) and then investigated in more detail by Bouma (1973) and in other early crowding studies: Chastain (1982), Krumhansl (1977), Krumhansl and Thomas (1977), and Wolford and Hollingsworth (1974). Although many recent vision studies of crowding have ignored this hallmark anisotropy, two studies have noted its presence in feature recognition (Bex, Dakin, & Simmers, 2003; Legge, Mansfield, & Chung, 2001).

Pelli et al. (2004) suggested the spatial scaling of crowding with eccentricity and its independence of stimulus size as the diagnostic test for crowding. Petrov et al. (in press) argued that the inward–outward anisotropy of crowding is a more appropriate diagnostic test. We also noted that details of V1 anatomy cannot explain the anisotropy. If anything, the magnification factor would predict an opposite effect.

Ecological factors, which could underlie the observed anisotropy, include optic flow and saccadic eye movements. Optic flow caused by locomotion is, on the average, directed outward, whereas optic flow caused by saccades is always inward along the direction to the saccadic target. We hypothesize that the saccadic optic flow might be more relevant to crowding anisotropy than locomotion optic flow because the latter grows with the square of eccentricity, whereas crowding increases linearly.

**Crowding mechanisms**

Here, we discuss various mechanisms of crowding suggested in the past and ask whether these mechanisms can explain the results of the triplet identification experiment.

**Local inhibition between similar features**

This class of crowding mechanisms involves local inhibition similar to the one found for surround suppression but, possibly, happening at a later stage (Chung et al., 2001; Estes, 1972, 1974). Surround suppression should be included in this list, as surround suppression and crowding have many similarities, and surround suppression could, in principle, cause crowding by eliminating weak but important features of the target (e.g., the difference between letters G and C). The lateral inhibition model was inspired by an observation that similar letters produce stronger crowding (Estes, 1972).

This class of explanations fails to account for the two main results of the present study. Firstly, it does not explain the strong inward–outward anisotropy. In our preceding study, we showed that surround suppression is isotropic in this respect (Petrov et al., in press). Thus, it is not surround suppression that causes crowding. Arguably, lateral inhibition could happen at a later stage than surround suppression and, thus, could have an inward–outward anisotropy even if surround suppression lacks it. Secondly (and more important), if we assume that the high-contrast Gabor patches used in our study could suppress one another to such an extent that orthogonal orientations were confused, perceived contrast of the Gabor patches would...
be dramatically reduced. In fact, no such effect was observed. As noted by Pelli et al. (2004), in crowding, the signal remains visible but becomes ambiguous. Moreover, because the lateral inhibition models assume that the inhibition operates between similar features, triplets with similar elements would be crowded more strongly than triplets with distinct elements. Thus, all elements of the $\backslash\backslash$ triplet will inhibit each other, and, as a result, the triplet would be one of the hardest to identify. Moreover, elements of the $\backslash/\backslash$ triplet should not cause any local suppression at all. In fact, the opposite confusion pattern was observed: The $\backslash/\backslash$ triplet was almost never confused (4%), whereas the $\backslash/\backslash$ triplet was confused 37% of the time. Also, the $/\backslash$ triplet was confused with $\backslash/\backslash$ and $\backslash/\backslash$ triplets, not vice versa (Confusion Pattern iii), whereas the inhibition explanation would predict the contrary.

Local pooling of individual features

Levi et al. (2002) and Pelli et al. (2004) argued that signal processing happens in two stages in the periphery. At the first stage, individual features are detected and surround suppression occurs. At the second stage, the feature information is pooled over an area of visual field proportional to the stimulus eccentricity, which results in crowding. To support this hypothesis, Levi et al. indicate that observers could easily detect the Gabor patches that compose their targets under conditions where crowding was strong. He et al. (1996) used adaptation to grating stimuli to show that detection and crowding are happening at different processing stages.

The pooling is, presumably, due to the limited resolution capacity of visual system in the periphery (Barlow, 1981; Levi & Klein, 1985; Neri & Levi, 2006) or, alternatively, due to the limited attentional resolution (He et al., 1996; Pöder, 2006). However, the mechanism of spatial pooling was not elaborated in these studies.

Wilkinson et al. (1997) proposed pooling as a part of texture detection mechanism. Because pooling in their model happens only when several iso-oriented elements are present in the same location, it is not clear how such texture-based pooling could explain crowding for stimuli used here and for stimuli in our preceding study shown in Figure 3, where crowding was produced by, essentially, a single orthogonal Gabor.

Here, we ask what kind of pooling could explain our results.

Superficially, the spatial pooling can be understood as a “what, but not where” phenomenon: Individual features are preserved, but information about their location is lost. In this scenario, the observers perceived slants of all Gabor elements in the target triplet but could not tell in which order the slants were arranged. This mechanism explains why the $\backslash\backslash$ triplet was rarely confused with other triplets, because in this case, the order did not matter. However, the “what but not where” explanation contradicts Experimental Finding II: When observers made an error, it was not just a matter of confusing the order of the triplet elements. Observers were at chance about the triplet orientation total (or.)—they were not able to tell how many elements were slanted to the left and how many were slanted to the right.

Anisotropic mislocalization model

Krumhansl (1977) and Krumhansl and Thomas (1977) proposed a crowding model, which explicitly incorporated the inward–outward anisotropy. The model combines the Estes (1972) local inhibition model and Wolford (1975) feature perturbation model. Chastain (1986), Krumhansl and Thomas (1976), and Wolford observed that peripheral features tend to be mislocalized toward the fixation. Wolford argued that features of outward characters are mislocalized to mix with inward characters, creating a feature perturbation (crowding) effect. No elaboration of “feature perturbation” was given. If we assume that the outward characters (or their features) were, indeed, mislocalized toward the fovea (i.e., perceptually shifted in this direction) and mixed with the inward characters, it would explain the resulting crowding of the inward characters but would also erroneously predict a similar amount of crowding for the outward character. Thus, the mislocalization explanation appears to defeat its purpose.

Anisotropic duplication model

We can assume, instead, that the outward features were duplicated and mixed with the inward characters rather than just mislocalized (i.e., shifted). This would explain how the outward feature crowds the inward features but, at the same time, remains identifiable itself. Yet, this model blatantly contradicts our everyday experiences. The model predicts that all peripheral objects would appear doubled!

Anisotropic pooling model

Instead of doubling, the outward feature could be pooled with the inward feature. This eliminates the “double-vision” problem because, now, both the inward and the outward features are required to induce crowding. Note, though, that this approach departs from the experimental findings of feature mislocalization, which inspired the Krumhansl (1977) and Wolford (1975) models.

The anisotropic pooling model provides an accurate account of some crowding properties in our study. It explains Confusion Patterns i and ii (including the confusion asymmetry between $/\backslash$ and $\backslash/\backslash$ triplets) as well as Result II (because individual orientation is no longer preserved in this scenario) and accounts, at least in an ad hoc fashion, for the inward–outward anisotropy of crowding (Result I).

Although the anisotropic pooling appears to explain some experimental findings in our study, it fails to
Anisotropic feature contrast model

Although the anisotropic pooling model gives erroneous predictions, there might be a grain of truth in it. We propose the following modification: Instead of one feature overwriting the other, the outcome of the anisotropic spatial pooling is such that only the presence (\(\ast\)) or absence (\(\sim\)) of the feature contrast (with respect to the outward feature) is stored at each site within the triplet. It is also understood that if the outward feature was absent, no pooling happened, and the original feature was preserved.

This anisotropic feature contrast model successfully explains the Confusion Patterns i–iii observed in our study:

i. The \(\begin{array}{l} \\setminus \end{array} \begin{array}{l} \sim \end{array}\) triplet was never confused with the remaining triplets: \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array} \begin{array}{l} \ast \end{array}\), \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array} \begin{array}{l} \sim \end{array}\), and \(\begin{array}{l} \ \begin{array}{l} \\setminus \end{array} \end{array} \begin{array}{l} \ast \end{array}\), and vice versa, because the other triplets had at least one site of orientation contrast, whereas the target triplet had none.

ii. The largest confusion was between \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array} \begin{array}{l} \ast \end{array}\) and \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array} \begin{array}{l} \sim \end{array}\) triplets because these were the only two triplets with the same number of contrast sites \((n = 1)\). We suggest that the \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array} \rightarrow \begin{array}{l} \vee \end{array}\) confusion was significantly more common than that in the opposite direction because the \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array}\) element of the \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array}\) triplet was outward with respect to the remaining elements and, thus, could crowd them both, creating two possible contrast sites: \(\ast\) and \(\sim\) (and, occasionally, \(\ast\sim\leftarrow\)). On the other hand, both \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array}\) elements of the \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array}\) triplet were outward with respect to the remaining element, which could create only one possible contrast site: \(\ast\).

iii. The \(\begin{array}{l} \ \begin{array}{l} \\setminus \end{array} \end{array} \begin{array}{l} \ast \end{array}\) triplet was occasionally confused to an equal degree with both \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array} \begin{array}{l} \ast \end{array}\) and \(\begin{array}{l} \ \begin{array}{l} \vee \end{array} \end{array} \begin{array}{l} \sim \end{array}\) triplets because its two contrast sites could be mistaken for the single contrast site of either triplet.

Thus, observers frequently confused one-contrast triplets among themselves, occasionally confused the two-contrast triplet with either of the one-contrast triplets, and almost never confused the no-contrast triplet with any other or vice versa. Because detection of orientation contrast is an easier task than orientation contrast discrimination (i.e., one contrast site vs. two contrast sites here), the anisotropic feature contrast model explains our data quite well. Besides accounting for all the confusion patterns, the model explains Result II: The triplet orientation total cannot be identified because the actual orientation is preserved for the outward element only.

Open questions

Although the proposed feature contrast model gives a parsimonious explanation of our results, it incorporates anisotropy (Result I) in an ad hoc fashion: It does not explain why the proposed feature contrast operation is directed toward the fovea. More research is necessary to determine the origin of the crowding anisotropy. Thus, Chastain (1982, 1985) and Krumhansl and Thomas (1977) reported that anisotropic crowding was observed only for nonconfusable characters (e.g., P and M), whereas for confusable characters (e.g., P and R), crowding from an inward mask was almost as strong as from the outward mask. We will attempt to replicate this effect with Gabor stimuli by reducing orientation difference of the triplet Gabors (which will make them more confusable).

Kooi, Toet, Tripathy, and Levi (1994) reported that crowding was significantly reduced when the target letter differed from distractors either in contrast polarity or in binocular disparity. Pöder (2006) observed that by increasing the number of distractors, the crowding effect on a color-defined target was reduced. Because the color contrast between target and distractors was effectively augmented when the number of distractors was increased, both studies suggest that increased feature contrast reduces crowding. This is expected if crowding spares strong feature contrast, which lends support to the model proposed here.

Because the feature contrast generally “pops out” preattentively, this supports the class of models that explain crowding by some constraints or limitations of attentional resolution. We hypothesize that only the preattentive feature contrast is preserved in crowding because the rest of visual information, which is later pooled within an (anisotropic) area of visual attention, is lost. He et al. (1996) and Intriligator and Cavanagh (2001) studied spatial resolution of visual attention and found multiple similarities between crowding and attentional resolution. Visual attention was shown to have the same radial–tangential anisotropy as crowding, but the possibility of the inward–outward anisotropy was not investigated in these studies. We are planning to test for this possibility in a study of
visual attention. If such an anisotropy is found, it would argue strongly that attentional resolution underlies the crowding phenomenon.

Conclusions

The aim of this study was to determine what kind of information is lost in crowding. Gabor stimuli, which are more tractable than letters, allowed us to analyze confusion patterns arising in crowding and demonstrate that no trivial loss of individual feature information can explain the phenomenon. We argue, instead, that the dissimilarity between a given Gabor and its outward neighbor was the only information available to observers. The proposed anisotropic feature contrast model accurately and parsimoniously accounts for the results of this study and supports the hypothesis that crowding is caused by limitations of attentional resolution.

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