On the generality of crowding: Visual crowding in size, saturation, and hue compared to orientation

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Perception of peripherally viewed shapes is impaired when surrounded by similar shapes. This phenomenon is commonly referred to as “crowding”. Although studied extensively for perception of characters (mainly letters) and, to a lesser extent, for orientation, little is known about whether and how crowding affects perception of other features. Nevertheless, current crowding models suggest that the effect should be rather general and thus not restricted to letters and orientation. Here, we report on a series of experiments investigating crowding in the following elementary feature dimensions: size, hue, and saturation. Crowding effects in these dimensions were benchmarked against those in the orientation domain. Our primary finding is that all features studied show clear signs of crowding. First, identification thresholds increase with decreasing mask spacing. Second, for all tested features, critical spacing appears to be roughly half the viewing eccentricity and independent of stimulus size, a property previously proposed as the hallmark of crowding. Interestingly, although critical spacings are highly comparable, crowding magnitude differs across features: Size crowding is almost as strong as orientation crowding, whereas the effect is much weaker for saturation and hue. We suggest that future theories and models of crowding should be able to accommodate these differences in crowding effects.

Keywords: crowding, masking, critical spacing, integration fields, feature pooling, anisotropy, information visualization, peripheral vision, object recognition, feature integration

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Introduction

A shape presented in the visual periphery is harder to identify when it is surrounded by other shapes. This phenomenon is commonly known as “crowding”. Importantly, crowding differs from “ordinary masking” in that target and mask signal do not necessarily have to overlap to have an effect. Since Korte (1923) originally described letter crowding, a substantial number of studies have established it to be a robust phenomenon that occurs across a broad range of conditions (for a review, see Strasburger, 2002). In addition, there is a growing body of evidence showing that crowding affects identification of relatively elementary orientation information as well (Andriessen & Bouma, 1976; Parkes, Lund, Angelucci, Solomon, & Morgan, 2001; Wilkinson, Wilson, & Ellemberg, 1997).

The mechanisms underlying crowding as well as the physiological origins still remain to be elucidated. Current theories hinge on either bottom–up or top–down explanations. Bottom–up pooling and integration models propose that objects and features detected in the periphery are integrated (pooled) over relatively large areas of visual space (Andriessen & Bouma, 1976; Parkes et al., 2001; Wilkinson et al., 1997), recently coined “integration fields” (Pelli, Palomares, & Majaj, 2004). Although the pooling model has proven successful in explaining the results of the referred studies, there are also studies in which this is not the case (e.g., Solomon, Felisberti, & Morgan, 2004). In addition to this bottom–up model, an alternative, attention-based model has been proposed. This model explains crowding as resulting from the limited spatial resolution of an attentional filter assumed to operate beyond the primary visual cortex (e.g., He, Cavanagh, & Intriligator, 1996; Montaser-Kouhsari, &

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Rajimehr, 2005; Tripathy & Cavanagh, 2002). Recently, Strasburger (2005) proposed a model that unifies both ideas, based on a distinction between transient and sustained visual attention, stating that the concept of "feature integration field" can be identified with "sustained attentional spotlight".

While rooted in observations from letter and orientation crowding experiments, the above explanations are sufficiently general to suggest that crowding could affect all visual features. Indeed, on the basis of circumstantial evidence from visual search experiments previously performed in our group, we inferred that crowding magnitude differs across features, with stronger crowding for size and orientation and weaker crowding for hue (Hannus, van den Berg, Bekkering, Roerdink, & Cornelissen, 2006). However, those experiments were not designed to systematically study this issue. Here, we report on two experiments investigating whether and how crowding affects the identification of orientation, size, saturation, and hue (because orientation has been extensively studied, this feature will serve to benchmark the effects found in other features). See Figure 1 for illustrative examples of crowding in these features.

Apart from a disagreement on the mechanism underlying crowding, what further complicates research on crowding is that there is no generally accepted definition for the phenomenon. Yet, several previous studies demonstrated that critical spacing (i.e., the largest target–mask spacing for which crowding occurs) for orientation and letter crowding consistently equals roughly half the target eccentricity (Bouma, 1970; Toet & Levi, 1992) and is independent of stimulus size (Levi, Hariharan, & Klein, 2002; Strasburger, Harvey, & Rentschler, 1991). Recently, Pelli et al. (2004) demonstrated that the exact opposite holds for ordinary masking, which scales with signal size, independent of eccentricity. In view of this, they proposed that the ultimate criterion for the presence of crowding is that critical target–mask spacing scales with eccentricity and is independent of signal size. We adopted this criterion to evaluate our results.

In the first experiment, we tested for which features identification thresholds increase with decreasing target–mask spacing. The second experiment additionally examined the influence of signal size.

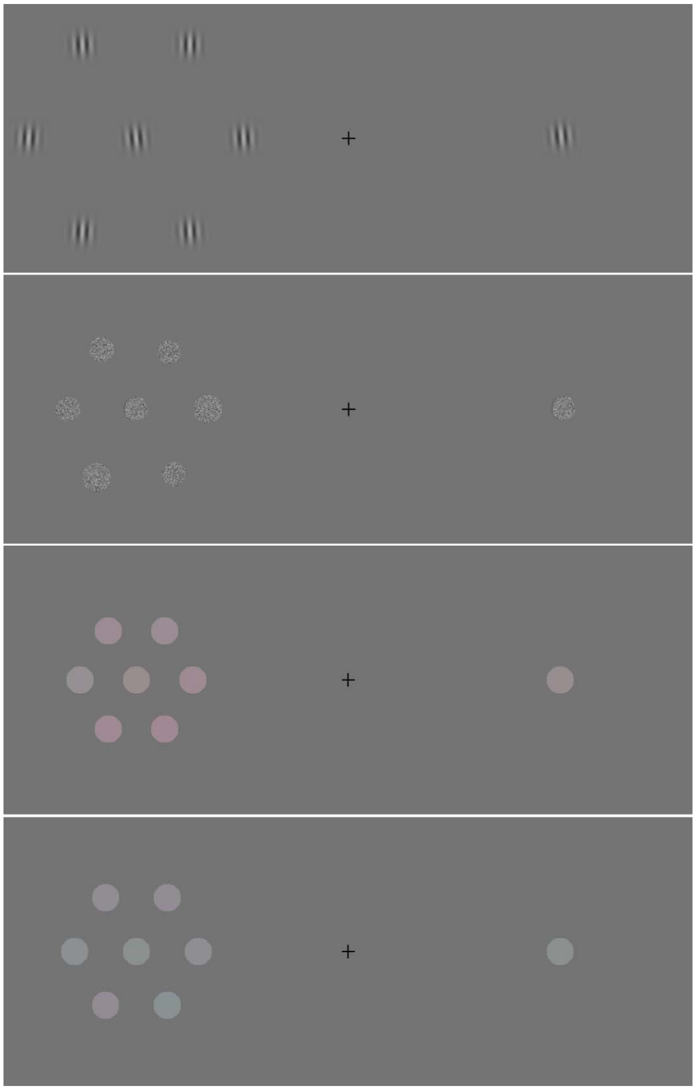

Figure 1. Examples illustrating crowding in the orientation, size, saturation, and hue domains. When fixating the cross, the masks make identification of target (central item) tilt, size, saturation, and hue more difficult. Target–mask spacings in these images were chosen such that the identification thresholds for all features are approximately doubled compared to identification of targets presented in isolation (when the viewing distance is such that the target is at 6° of eccentricity). Based on results of Experiment 1.

Methods

Participants

A total of four participants took part in the experiments. Participants B.P.W. and J.D. were paid and were naive to the purpose of the experiments. Participant M.D. was informed about the purpose of the experiments only after he completed Experiment 1. Participant R.B. is an author. Table 1 gives an overview of the experiments and the participants.

Apparatus

Stimulus generation and data collection were done using Matlab in combination with the Psychophysics and Eyelink Toolbox extensions (Brainard, 1997; Cornelissen, Peters, & Palmer, 2002; Pelli, 1997). Stimuli were

Experiment	Features	Eccentricities (deg)	Size (deg)	Participants
1	Ort, size, sat, hue	0, 6, 10	0.8	B.P.W., M.D., R.B.
2	Ort, size, sat, hue	2, 4	0.4	M.D., R.B.
2	Ort, size, sat	0	1.5	J.D., M.D., R.B.
2	Ort, size, sat, hue	6, 10	1.5	J.D., M.D., R.B.
2	Ort, size, sat, hue	15	1.5	M.D., R.B.

Table 1. Overview of the experiments and the participants (ort = orientation; sat = saturation).

displayed on a 22-in. LaCie RGB monitor with a 10-bit resolution per color channel. The viewing distance was 60 cm. A chin rest was used to reduce head movements.

Tasks and stimuli

The sequence of stimuli for both experiments is depicted in Figure 2. It consisted of the following: display of reference patch (400 ms), a noise mask (100 ms), fixation cross (900 ms), target and masks (200 ms) followed by a second noise mask (100 ms), and, finally, a blank response screen. The task was to identify the modulation direction of the target (always the central patch) compared to the reference. Fixation was always at the same location (a little right of screen center), and stimuli were presented to the left of this. No performance feedback was given to the participants. Stimuli were presented against a gray background (18 cd/m^2).

Orientation

Orientation stimuli consisted of gratings with 50% contrast and a fixed phase convolved with a Gaussian. The spatial frequency of the gratings depended on the size of the stimuli. It was always chosen such that approximately 3 cycles were visible (4.0 cpd in Experiment 1; 6.9 and 2.4 cpd in Experiment 2, for small and large stimuli, respectively). Reference orientation was vertical. Modulation of the target and mask orientations was achieved by rotating the grating. Participants judged whether target orientation was tilted to the left or right compared to the reference.

Size

Size stimuli were discs with an achromatic random dot pattern with a mean luminance of 22 cd/m^2. Sizes were defined in terms of disc radii, and the reference size varied across experiments (see below). Increasing and decreasing the radii of the patterns modulated size. Participants judged whether target size was smaller or larger compared to the reference.

Hue

Hue stimuli were uniform, equiluminant red or green discs. Red was produced by increasing the output of the red channel relative to the reference gray and simultaneously decreasing the output of the green channel, thus keeping disc luminance fixed. Green was produced analogously, by decreasing the output of the red channel and increasing the output of the green channel. To further increase color resolution, we used a dithering method: Half of the pixels of a disc were modulated while the other half remained gray (dithering was done in a regular but imperceptible checkerboard grid). This resulted in smaller hue modulation steps, thus allowing for more accurate threshold measurements. Participants judged whether target hue was greener or redder than the reference gray. In terms of CIE (1931) coordinates, hues varied from $x = 0.233$, $y = 0.320$ (greenest) to $x = 0.307$, $y = 0.296$ (reddest).

Saturation

Saturation stimuli were identical to the hue stimuli, with the difference that the reference color was red. Modulation of saturation was achieved with the procedure described above. The reference red was produced by a +40% modulation relative to the neutral gray. Participants judged whether the target was less or more saturated than the reference. In terms of CIE, red colors in the saturation experiments varied from $x = 0.278$, $y = 0.309$ (least saturated red) to $x = 0.302$, $y = 0.299$ (most saturated red).

Mask modulation

In a pilot experiment (see Supplementary Material), we found that orientation-identification thresholds increase with increasing mask variance. Consequently, to allow comparison of effect sizes across features, for the main experiments, we matched mask variance across features as follows. For each participant and for each feature, we measured the target contrast required for a performance of 75% correct responses in a condition with a target–mask spacing of 2° and six masks that were identical to the reference. Target and masks were presented at 8° eccentricity. In the actual experiments, the thresholds thus

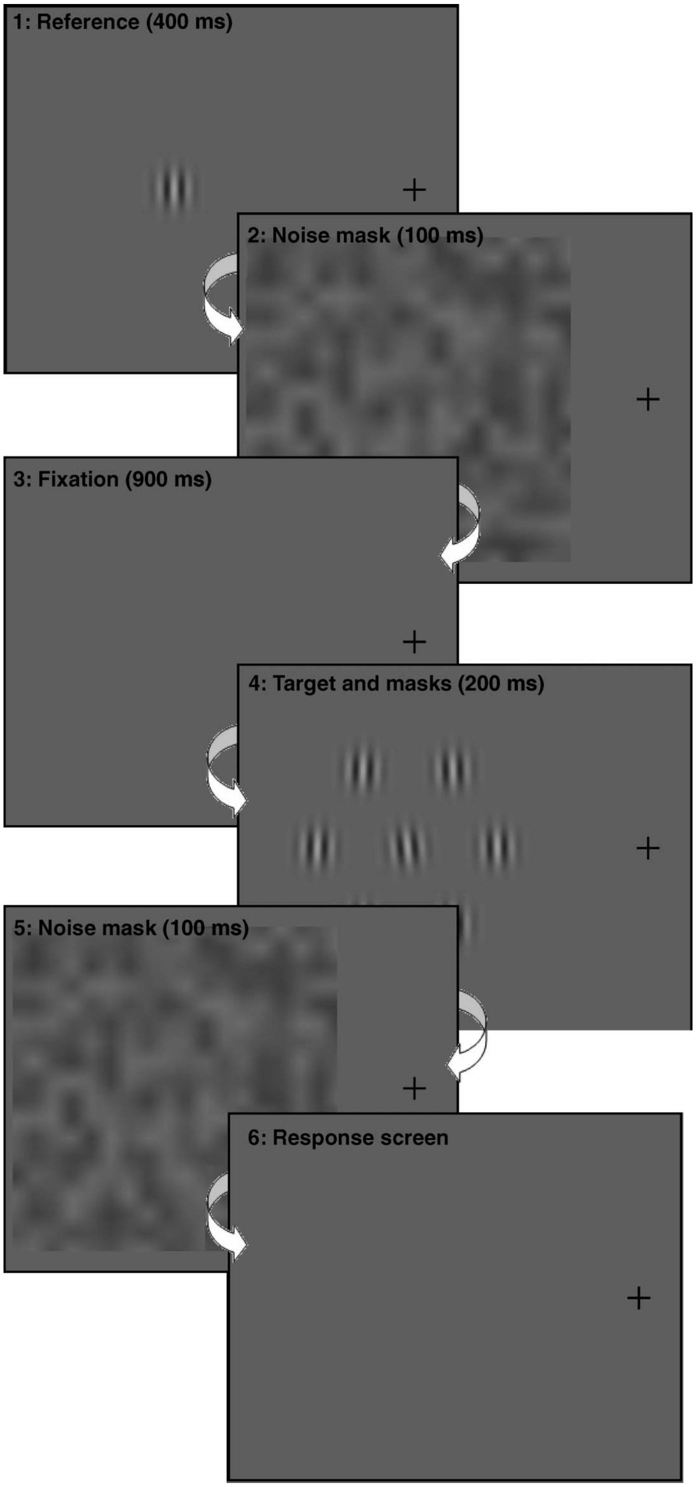

Figure 2. Schematic illustration of an orientation trial.

found defined the limits of the range from which mask values were drawn (uniformly).

To illustrate this, suppose that using the above procedure, for a particular participant, a tilt threshold of 5° from vertical was found. Then, with a reference orientation of 90° (vertical), masks in the actual experiments of this participant would have random orientations uniformly drawn from the 85–95° range. The values actually used in the experiments are listed in Table 2.

Measurement of thresholds

We used the QUEST staircase procedure (King-Smith, Grigsby, Vingrys, Benes, & Supowit, 1994; Watson & Pelli, 1983) to determine the 75% correct performance level of a Weibull function. Slope parameter β was set to 3.5° deg^{-1}, and guess rate γ was set to 0.50 (making the performance range effectively 50–100%). Thresholds were determined based on measurements of 40 trials; each threshold was measured twice per participant and averaged.

Analysis

Following Pelli et al. (2004), we analyzed two aspects of the (sigmoidal) threshold-spacing curves: critical spacing (i.e., the largest spacing at which there is a threshold elevation) and total threshold elevation. To determine these values, we fitted a very simple model to the data relating spacing to threshold. The model consisted of a threshold ceiling, a threshold floor, and a linear transition between these two (Figure 3). Fitting was done using a least squares method. Critical spacing was computed as the second point of discontinuity in the slope of the fit, and threshold elevation was computed as the ratio between the fit ceiling and floor.

Experiments

Experiment 1—Effect of nearby masks on identification thresholds

Although there is no consensus about the exact definition of crowding, it is safe to say that to be considered a candidate for crowding, a feature should, at the very least, possess the property that nearby masks impair its identification. In this experiment, we determined

Participant	Orientation (deg)	Size (deg)	Saturation (%)	Hue (%)
B.P.W.	5.2	0.11	6.0	11.3
J.D.	4.0	0.17	7.0	N/A
M.D.	2.9	0.13	15.0	15.0
R.B.	3.2	0.11	11.1	10.9

Table 2. Maximum mask modulation values for each participant. Sizes were defined as disk diameter. Saturation and hue modulations were achieved by modulating the output of the red and green display channels with a specified percentage (see text).

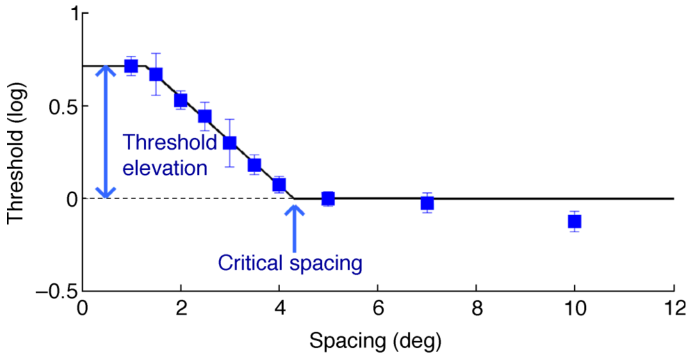

Figure 3. Illustration of how the data were analyzed. Threshold elevations and critical spacings were determined by fitting a clipped line to the data.

size, hue, and saturation identification thresholds for a range of target–mask spacings. Orientation was included as well, both to validate our paradigm and to serve as a benchmark for possible effects in the other features. Targets were presented at 0°, 6°, and 10° of eccentricity and were surrounded by six equally spaced masks. All hue and saturation stimuli had a size of 0.8°. Also, the reference size in the size conditions was 0.8°. For creation of the orientation stimuli, the variance of the Gaussian filter was chosen such that the resulting grating patches were perceptually of similar size as the disc stimuli used for the other features. Measurements were performed in blocks of 200 trials. In every block, thresholds were measured for five different spacing/eccentricity combinations for a single feature (five staircases randomly interleaved).

Experiment 2—Influence of stimulus size

The second experiment was identical to Experiment 1, except that different stimulus sizes were used and a number of additional target eccentricities were included. Identification thresholds were measured for stimuli of 0.4° presented at 0°, 2°, and 4° of eccentricity and for stimuli of 1.5° presented at 0°, 6°, 10°, and 15° of eccentricity. These data, combined with those from Experiment 1, provide information about how critical spacing and threshold elevation relate to target eccentricity and stimulus size. On the basis of this information, we can assess whether the features under study meet the crowding criterion recently proposed by Pelli et al. (2004).

Results

Experiment 1

In the first experiment, we examined the influence of spacing and eccentricity on feature identification threshold.

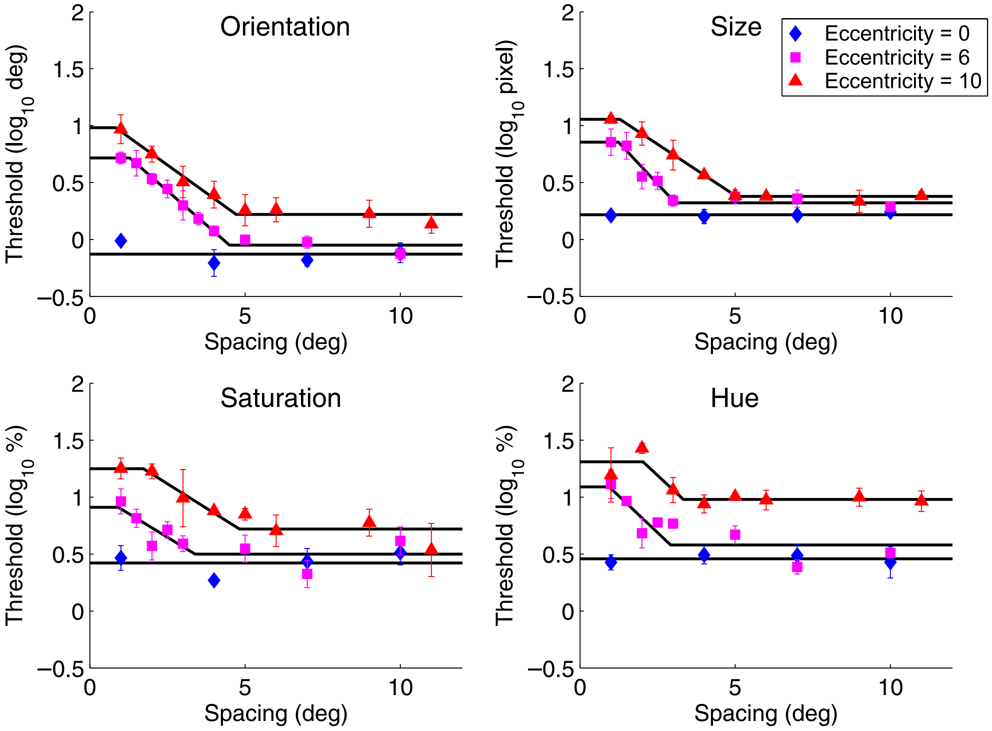

Figure 4. Target identification threshold as a function of target–mask spacing for orientation, size, saturation, and hue (Experiment 1). Data were averaged over participants (bars represent standard errors). Stimuli subtended 0.8° of visual angle.

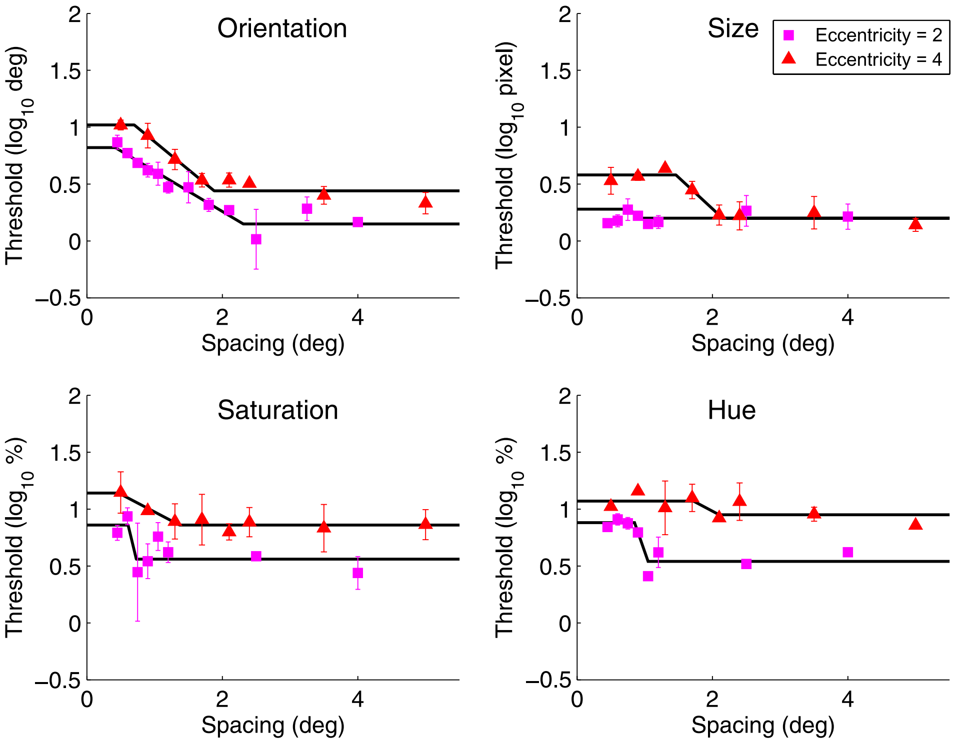

Figure 5. Target identification threshold as a function of target–mask spacing for orientation, size, saturation, and hue (Experiment 2). Data were averaged over participants (bars represent standard errors). Stimuli subtended 0.4° of visual angle.

The group results are presented in Figure 4. It shows that for all features, the threshold for identifying peripheral targets starts to increase once target–mask spacing is below a certain critical spacing. When targets are presented foveally (i.e., at 0° eccentricity), none of the features show obvious threshold elevation for any mask spacing.

Experiment 2

In the second experiment, we examined the influence of stimulus size on critical spacing and threshold elevation. Results for small and large stimuli are shown in Figures 5 and 6, respectively. As in Experiment 1, in most cases, we observe clear relationships between spacing and identification threshold. Note that for some of the smallest stimuli, this relationship was less obvious. A possible explanation is that at small eccentricities, crowding effects were only small and got obscured due to a relatively low signal-to-noise ratio.

Next, to evaluate our results against the crowding criterion proposed by Pelli et al. (2004), we determined critical spacings for each participant individually and for all features, stimulus sizes, and eccentricities. In a few cases, no proper fit could be made. This was the case for the size and hue data of M.D. from the experiment with small stimuli, size data of J.D. for large stimuli, saturation data of M.D. for large stimuli, and hue data of R.B. for large stimuli (at eccentricities of 2°, 4°, 6°, 6°, and 6°, respectively). These data points (approximately 7% of all data) were not included in the figures and analyses below.

Figure 7 shows critical spacing as a function of eccentricity. The *y*-intercept of the linear fits was fixed to zero, motivated by the observation that foveally presented targets showed no threshold increase.

Threshold elevation (ceiling/floor ratio) can be seen as a measure of crowding strength. Figure 8 shows scatter plots of threshold elevation as a function of eccentricity. Although the R^2 values of the linear fits are rather small, not one of them is negative. Hence, it appears that for all features, threshold elevation tends to increase with eccentricity.

To facilitate comparison over features, we computed the median threshold elevation for each feature (Figure 9). From this, we can make two observations. First, threshold elevations for orientation and size are comparable, as well as those for hue and saturation. Second, threshold elevations for orientation and size are considerably larger than those for saturation and hue. To check for statistical significance of the second observation, we combined the orientation and size data and the saturation and hue data and performed a Wilcoxon rank sum test. This shows that the difference in medians from the

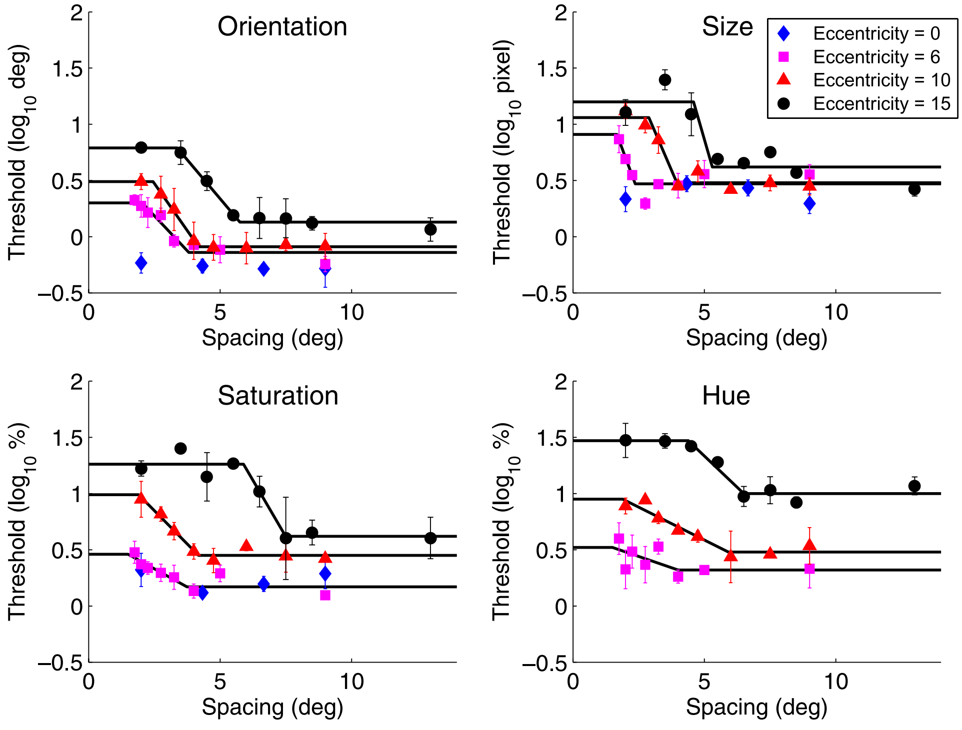

Figure 6. Target identification threshold as a function of target–mask spacing for orientation, size, saturation, and hue (Experiment 2). Data were averaged over participants (bars represent standard errors). Stimuli subtended 1.5° of visual angle. For clarity, the model fits for data from the zero eccentricity condition are not shown.

orientation data combined with the size data significantly differs from that of the combined saturation and hue data ($p < .001$).

Discussion

Our main finding is that all features tested here meet the minimum criterion for crowding: Identification of targets uniquely defined by one of these features is impaired by nearby masks defined by the same feature. One may ask whether the threshold elevations reported on here should indeed be classified as crowding, rather than surround suppression or "ordinary masking" effects. This depends on what specific definition of crowding one employs, which is currently still a matter of debate. Recently, two competing "diagnostic criteria" were proposed for crowding, one by Pelli et al. (2004) and the other by Petrov, Popple, and McKee (2007). Regarding the latter criterion, an anisotropy in the effect of foveally versus peripherally presented masks, we were unable to reproduce this finding for orientation crowding (see Supplementary Material for a detailed description of these experiments). Hence, we decided not to evaluate the other features on this criterion. Next, we therefore discuss our data only in the light of the criterion that was proposed by Pelli et al.

Critical spacing scales with eccentricity, independent of size

As mentioned in the Introduction section, according to Pelli et al. (2004), the definitive criterion for crowding is that critical spacing scales with eccentricity, independent of signal size. Regarding the scaling of critical spacing with eccentricity, our results strongly indicate that this is the case for all features tested here (results are summarized in Figure 7). The second part of the criterion of Pelli et al. requires critical spacing to be independent of signal size. As noted by Pelli et al., an issue with many studies that varied signal size and eccentricity is that both aspects were covaried, making it difficult to disentangle size effects from eccentricity effects (and, consequently, making it impossible to assess whether the scaling of critical spacing with eccentricity is size independent). Our measurements at 6° and 10° of eccentricity were repeated for different stimulus sizes and, thus, can be drawn upon to address the question of size independence. The scatter plots in Figure 7 do not show a clear size-related clustering at these eccentricities and, therefore, confirm that for the features

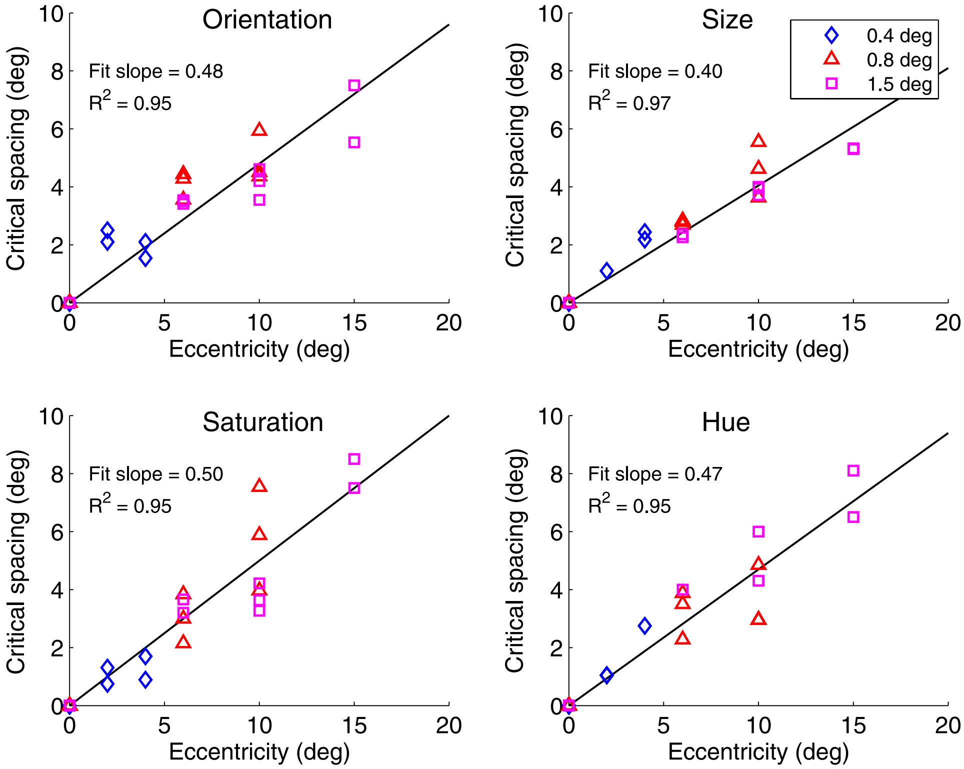

Figure 7. Critical spacing as a function of eccentricity for orientation, size, saturation, and hue (based on combined data from Experiments 1 and 2; critical spacings were determined for each individual participant). Results are split by target size. The lines show least-squared error linear fits. Note that the *y*-intercept of the linear fits was fixed to zero, motivated by the observation that foveally presented targets showed no threshold increase for any target size.

at stake, critical spacing does not depend on stimulus size. Moreover, in a pilot experiment (see Supplementary Material), we measured threshold elevation as a function of mask spacing for three different stimulus sizes. Critical spacings were nearly identical for all stimulus sizes, adding further support for this conclusion.

Altogether, our results show that for all features considered here, critical spacing scales linearly with eccentricity and is independent of stimulus size. Following the criterion put forward by Pelli et al. (2004), this means that our results show that crowding affects identification of size, hue, and saturation and, thus, is not restricted to character and orientation identification. As an interesting aside, we note that not only does critical spacing scale linearly with eccentricity, but it consistently does so with a slope of approximately 0.5. This shows that Bouma's rule of thumb, which states that "critical spacing is roughly half the eccentricity" (Bouma, 1970), holds not only for orientation but also for size, hue, and saturation.

Crowding magnitude

Results from previous experiments performed in our group (Hannus et al., 2006) provided circumstantial evidence for crowding in size and hue perception and suggested different effect strengths. In those experiments, we tested the extent to which features are processed independently in conjunction search. Participants searched for a cued target in a circular array with 12 distractors. Although we matched discriminability of the three features (resulting in symmetric performance in single feature search), asymmetries were found in conjunction search performance. When searching for color/orientation conjunctions, participants much more often judged color correctly than orientation. Also, for color/size conjunctions, participants performed better on size, although the asymmetry was smaller for these conjunctions. One of the possible explanations that we offered for these asymmetries was that crowding was stronger in conjunction search compared to single feature search (due to the presence of homogenous distractors in the former versus heterogeneous distractors in the latter) but with different effect strengths across features. We predicted that crowding was strongest for orientation, somewhat weaker for size, and weakest for color. Our present results are largely in line with these earlier inferences. Although we did not find a substantial difference between the effects for orientation and size, crowding in these features was indeed found to be much stronger than crowding in the color domain (results are summarized in Figures 8 and 9). This suggests

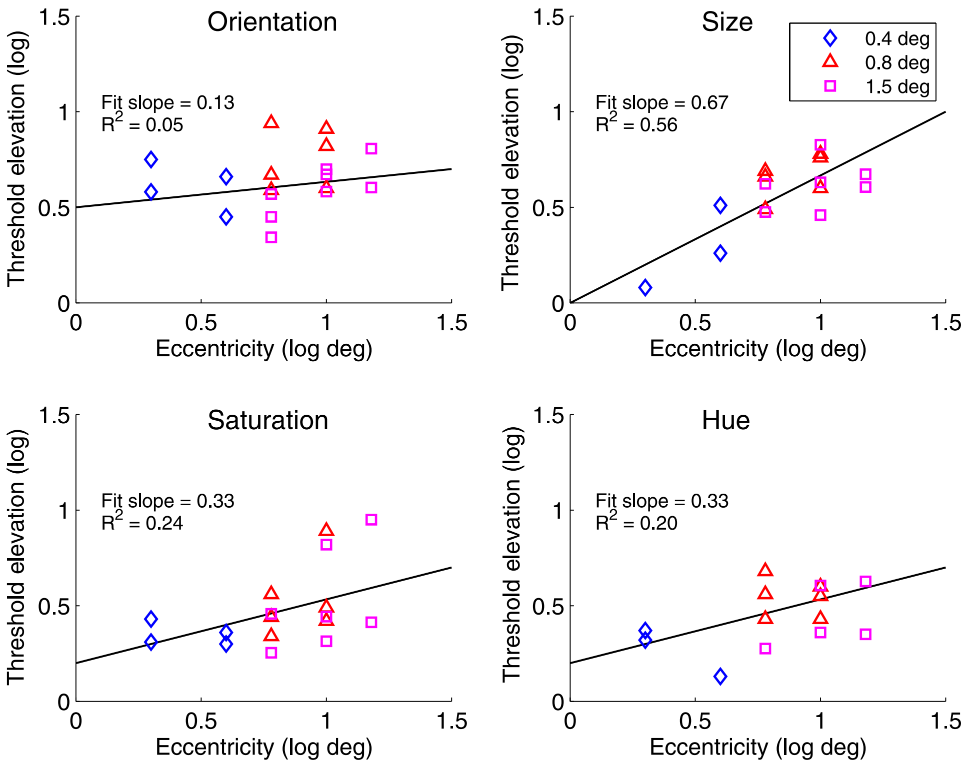

Figure 8. Threshold elevation as a function of eccentricity for orientation, size, saturation, and hue (based on combined data from Experiments 1 and 2; threshold elevations were determined for each individual participant). Results are split by target size. The lines show least-squared error linear fits.

that threshold elevation in crowding and performance degradation in conjunction search may, at least, partly be caused by the same underlying mechanism.

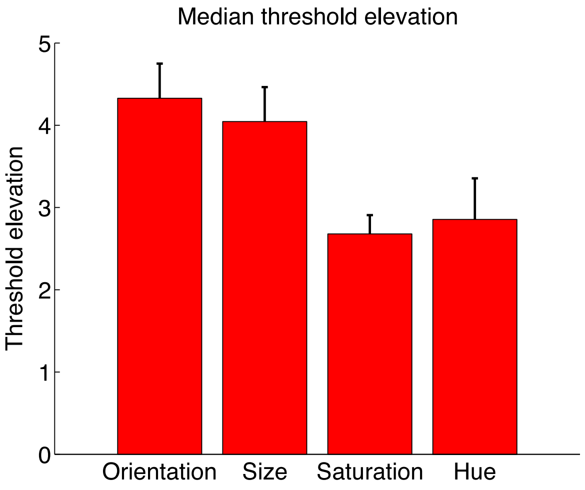

Figure 9. Median threshold elevations of different features. Compared to crowding in orientation and size, the effect is weak for saturation and hue. Shown are mean medians of 10,000 bootstrap samples. Error bars represent 1 *SD* around these bootstrapped means.

Orientation crowding and the tilt illusion

Solomon et al. (2004) distinguish two different ways in which masks can affect (peripheral) orientation identification: Masks can impair acuity (crowding) and can introduce a perceptual bias with opposite sign to the mask tilt (tilt illusion). When this bias fluctuates from trial to trial, it can cause a threshold increase, and this increase cannot be distinguished from crowding effects. In our experiments, we used stochastically defined masks, which, in addition to crowding, may have introduced a fluctuating bias. However, we will argue that biases were negligibly small in our experiments, if present at all.

Solomon et al. (2004) report strong bias effects for large mask tilts (22.5° and 45°). However, for tilts of 5° (the smallest tilt considered), 7 out of 12 estimated biases were not significantly different from 0, whereas the remaining 5 biases were very small (<1°). In our experiments, mask tilts were chosen randomly but within a limited range (with 0 as midpoint). Maximum tilt differed per participant but was always in the order of 3° to 5° (Table 2). This means that the average mask tilt must have been well below 5° in most trials. Assuming that biases in our experiments—if present—were largely determined by average mask tilt, it follows that these biases were smaller than those reported by Solomon et al. for the condition with masks with 5° of tilt. In other words, tilt biases in our experiments were most likely absent or very small.

Mechanisms underlying crowding

An integral part of our stimulus design was the presentation of a reference that served as a comparison stimulus. This reference, however, has the side effect of cueing the location of the target. If crowding is a purely attentional phenomenon, we would expect that location cueing diminishes the effect. However, for all features, we found critical spacings that are highly comparable to those found in previous studies with letter and orientation tasks (and that did not use location cueing; e.g., Bouma, 1970; Pelli et al., 2004; Toet & Levi, 1992). This is in line with a recent study by Scolari, Kohnen, Baron, and Awh (2007), who found that spatial cueing does not affect critical spacing. We agree with these authors that this argues against the idea that crowding is the sole result of attentional mechanisms and that it favors the idea that crowding is caused—at least partly—by hardwired bottom–up mechanisms, such as the hypothesized "integration fields" (Pelli et al., 2004). Anecdotally, however, we also note that none of our participants ever spontaneously reported seeing yellowish targets (rather than red or green) in the hue experiments. This argues against the idea that crowding is the result of a form of (bottom–up) averaging and suggests that it is more related to an inability to accurately localize features.

Crowding, salience, and information visualization

Unraveling the mechanisms behind crowding not only is important for understanding how the visual system works but also has a number of interesting applications. Theory about crowding could, for example, be used to design more effective information displays, which is one of the main goals in the research field of information visualization. Our results show that crowding is a rather general feature property, not restricted to perception of letters and orientations. Furthermore, findings from our earlier mentioned pilot study (see Supplementary Material) indicate that identification thresholds increase with mask variance. These findings predict that crowding is strong in information displays with high local feature variance. Interestingly, although arrived at from a different starting point and expressed in different terms, a similar argument was recently put forward by Rosenholtz, Yuanzhen, Mansfield, and Jin (2005) in their work on visual clutter modeling. Inspired by theories about feature salience, these authors constructed a model to predict clutter in a display, using local feature variance as a measure of "visual clutter" (Rosenholtz et al., 2005). Initial experimental results showed a considerable correlation between model prediction and subjective experience of clutter. On the basis of our current findings, we propose to go a step further and hypothesize that crowding is a main constituent of visual clutter. If so, we can predict from the results presented here that orientation and size variance cause more clutter than hue and saturation variance. In the context of information visualization, this implies that orientation and size are less suitable features for information encoding than hue and saturation. This would be compatible with what we concluded—on different grounds—in a previous study (Van den Berg, Cornelissen, & Roerdink, 2007). Furthermore, it would follow that, like crowding, visual clutter primarily affects peripheral vision (which, in turn, would be expected to impair the planning of effective eye movements in search displays). Further experiments are required to test these predictions.

Conclusion

Crowding is not specific to letter and orientation identification; it also affects perception of size, hue, and saturation of objects. Our results for these latter three features are strikingly comparable to those earlier found for letter and orientation crowding: Identification thresholds increase with decreasing mask spacing, and critical spacings are roughly half the eccentricity for all features that we tested. Furthermore, we found that effect sizes differ across features: Crowding of size is comparable to that of orientation, whereas crowding of hue and saturation is significantly weaker. Future theories and models of crowding should be able to accommodate these findings.

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References

Andriessen, J. J., & Bouma, H. (1976). Eccentric vision: Adverse interactions between line segments. *Vision Research, 16,* 71–78. [PubMed]

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226,* 177–178. [PubMed]

Brainard, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision, 10,* 433–436. [PubMed]

Cornelissen, F. W., Peters, E. M., & Palmer, J. (2002). The Eyelink Toolbox: Eye tracking with MATLAB and the Psychophysics Toolbox. *Behavior Research Methods, Instruments & Computers, 34,* 613–617. [PubMed]

Hannus, A., van den Berg, R., Bekkering, H., Roerdink, J. B., & Cornelissen, F. W. (2006). Visual search near threshold: Some features are more equal than others. *Journal of Vision, 6*(4):15, 523–540, http://journalofvision.org/6/4/15/, doi:10.1167/6.4.15. [PubMed] [Article]

He, S., Cavanagh, P., & Intriligator, J. (1996). Attentional resolution and the locus of visual awareness. *Nature, 383,* 365–370. [PubMed]

King-Smith, P. E., Grigsby, S. S., Vingrys, A. J., Benes, S. C., & Supowit, A. (1994). Efficient and unbiased modifications of the QUEST threshold method: Theory, simulations, experimental evaluation and practical implementation. *Vision Research, 34,* 885–912. [PubMed]

Korte, W. (1923). Über die Gestaltauffassung im indirekten Sehen. *Zeitschrift für Psychologie, 93,* 17–82.

Levi, D. M., Hariharan, S., & Klein, S. A. (2002). Suppressive and facilitatory spatial interactions in peripheral vision: Peripheral crowding is neither size invariant nor simple contrast masking. *Journal of Vision, 2*(2):3, 167–177, http://journalofvision.org/2/2/3/, doi:10.1167/2.2.3. [PubMed] [Article]

Montaser-Kouhsari, L., & Rajimehr, R. (2005). Subliminal attentional modulation in crowding condition. *Vision Research, 45,* 839–844. [PubMed]

Parkes, L., Lund, J., Angelucci, A., Solomon, J. A., & Morgan, M. (2001). Compulsory averaging of crowded orientation signals in human vision. *Nature Neuroscience, 4,* 739–744. [PubMed] [Article]

Pelli, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442. [PubMed]

Pelli, D. G., Palomares, M., & Majaj, N. J. (2004). Crowding is unlike ordinary masking: Distinguishing feature integration from detection. *Journal of Vision, 4*(12):12, 1136–1169, http://journalofvision.org/4/12/12/, doi:10.1167/4.12.12. [PubMed] [Article]

Petrov, Y., Popple, A. V., & McKee, S. P. (2007). Crowding and surround suppression: Not to be confused. *Journal of Vision, 7*(2):12, 1–9, http://journalofvision.org/7/2/12/, doi:10.1167/7.2.12. [PubMed] [Article]

Rosenholtz, R., Yuanzhen, L., Mansfield, J., & Jin, Z. (2005). Feature congestion: A measure of display clutter. In G. van der Veer & C. Gale (Eds.), *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (pp. 761–770). Portland, Oregon, USA: ACM.

Scolari, M., Kohnen, A., Barton, B., & Awh, E. (2007). Spatial attention, preview, and popout: Which factors influence critical spacing in crowded displays? *Journal of Vision, 7*(2):7, 1–23, http://journalofvision.org/7/2/7/, doi:10.1167/7.2.7. [PubMed] [Article]

Solomon, J. A., Felisberti, F. M., & Morgan, M. J. (2004). Crowding and the tilt illusion: Toward a unified account. *Journal of Vision, 4*(6):9, 500–508, http://journalofvision.org/4/6/9/, doi:10.1167/4.6.9. [PubMed] [Article]

Strasburger, H. (2002). *Indirektes Sehen: Formerkennung im zentralen und peripheren Gesichtsfeld.* Gottingen: Hogrefe-Verlag.

Strasburger, H. (2005). Unfocused spatial attention underlies the crowding effect in indirect form vision. *Journal of Vision, 5*(11):8, 1024–1037, http://journalofvision.org/5/11/8/, doi:10.1167/5.11.8. [PubMed] [Article]

Strasburger, H., Harvey, L. O., & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception & Psychophysics, 49,* 495–508. [PubMed]

Toet, A., & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research, 32,* 1349–1357. [PubMed]

Tripathy, S. P., & Cavanagh, P. (2002). The extent of crowding in peripheral vision does not scale with target size. *Vision Research, 42,* 2357–2369. [PubMed]

Van den Berg, R., Cornelissen, F. W., & Roerdink, J. B. T. M. (2007). Perceptual dependencies in information visualisation assessed by complex visual search. *Transactions on Applied Perception, 4*. Manuscript submitted for publication.

Watson, A. B., & Pelli, D. G. (1983). QUEST: A Bayesian adaptive psychometric method. *Perception & Psychophysics, 33,* 113–120. [PubMed]

Wilkinson, F., Wilson, H. R., & Ellemberg, D. (1997). Lateral interactions in peripherally viewed texture arrays. *Journal of the Optical Society of America A, Optics, image science, and vision, 14,* 2057–2068. [PubMed]