The crowding factor method applied to parafoveal vision

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Crowding increases with eccentricity and is most readily observed in the periphery. During natural, active vision, however, central vision plays an important role. Measures of critical distance to estimate crowding are difficult in central vision, as these distances are small. Any overlap of flankers with the target may create an overlay masking confound. The *crowding factor method* avoids this issue by simultaneously modulating target size and flanker distance and using a ratio to compare crowded to uncrowded conditions. This method was developed and applied in the periphery (Petrov & Meleshkevich, 2011b). In this work, we apply the method to characterize crowding in parafoveal vision (<3.5 visual degrees) with spatial uncertainty. We find that eccentricity and hemifield have less impact on crowding than in the periphery, yet radial/tangential asymmetries are clearly preserved. There are considerable idiosyncratic differences observed between participants. The crowding factor method provides a powerful tool for examining crowding in central and peripheral vision, which will be useful in future studies that seek to understand visual processing under natural, active viewing conditions.

Introduction

The gathering of visual information is limited by visual acuity (e.g., Weymouth, 1958) and crowding (Bouma, 1970, 1973; Hariharan, Levi, & Klein, 2005; Levi, 2008; Pelli & Tillman, 2008; Stuart & Burian, 1962; Townsend, Taylor, & Brown, 1971). Crowding, or a decrease in perception of an object's properties, occurs when a target object is surrounded or flanked by similar objects. The critical distance within which flankers begin to crowd the target object increases with the eccentricity of the target (Bouma's law; also see the revised Bouma's law in Rosen, Chakravarthi, & Pelli, 2014). Crowding is stronger and its effects are most readily observed in the periphery. As a result of this, the vast majority of studies test crowding at eccentricities outside of central vision by measuring the critical distance.

In the periphery, crowding depends on target-flanker configuration (Livne & Sagi, 2007, 2010), crowding is stronger when (a) the target-flanker configuration relative to the gaze is radial rather than tangential (Toet & Levi, 1992; Petrov & Meleshkevich, 2011a, 2011b), (b) target-flanker configuration is horizontal rather than vertical (Feng, Jiang, & He, 2007), and (c) the target is in the upper rather than lower hemifield (Fortenbaugh, Silver, & Robertson, 2015; He, Cavanagh, & Intriligator, 1996; Intriligator & Cavanagh, 2001). These effects are also shown to be quite idiosyncratic (Petrov & Meleshkevich, 2011a).

Crowding can occur for high-level visual processing, such as faces (Louie, Bressler, & Whitney, 2007), and low-level single-feature visual targets, such as Gabors (e.g., Hariharan et al., 2005), indicating that crowding occurs at all levels of visual processing. This affects the selection of objects for perception and/or action (e.g., selection of the next saccadic target), which affects saccade metrics and fixation durations (e.g., de Vries, Hooge, Wiering, & Verstraten, 2011; Moll & Jones, 2013; Vlaskamp & Hooge, 2006). In other words, saccade length distribution can be an indicator of the quality of visual information, with shorter saccades made when a target is in a more crowded environment (Vlaskamp & Hooge, 2006; de Vries et al., 2011). Saccade lengths measured in natural viewing environments follow a distribution that peaks around 3 to 4 visual degrees (vd) and falls off exponentially (Bahill, Adler, & Stark, 1975):

$$\text{Frequency} = 15e^{\left(-\frac{L}{7.6}\right)}$$

where L is saccade length.

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Integrating over this function, we find that the majority of saccades (55%) have amplitudes less than 5 vd, constraining the majority of visual samples to the central 10 vd of the visual field. Similarly, 32% of saccades are less than 2.5 vd, or the central 5 vd of the visual field. Thus, crowding in central vision is arguably more relevant to our natural perception of the world and may play a role in constraining saccadic planning.

There are studies that have looked at crowding in central vision with small eccentricities under static viewing conditions (e.g., Levi, Klein, & Aitsebaomo, 1985; Toet & Levi, 1992). In general, the observed effects of crowding for large eccentricities also hold in central vision: Crowding degrades performance and is stronger for radial rather than tangential target/flanker configurations. At an eccentricity of 1.2 vd, Grainger, Tydgat, and Isselé (2010) showed that, along the horizontal meridian, letter stimuli but not symbols are crowded more on the left than right of the gaze location. Bex, Dakin, and Simmers (2003) found that the crowding zone for moving targets is radially elongated for eccentricities as small as 2 vd. Using band-limited c-patterns composed of Gabor patches, Hariharan et al. (2005) showed that crowding depends on target size at the fovea but not at the periphery. Similar to crowding studies in the periphery, critical distance between flankers and targets is typically measured, which becomes increasingly difficult near the fovea.

We apply a technique first introduced by Petrov and Meleshkevich (2011b) to examine crowding in central vision. The *crowding factor (CF) method* compares threshold object discrimination in the presence and absence of flankers. The CF method takes care of target size and critical distance to flankers simultaneously: target/flanker size and center-to-center distance decreases with an increase in the spatial frequency of the target Gabor. The CF, defined as the ratio of discrimination threshold spatial frequencies in the unflanked to flanked conditions minus one, is the measure of crowding strength (Petrov and Meleshkevich, 2011a, 2011b). Using this method at 4 and 8 vd eccentricity, Petrov et al. demonstrated known hallmarks of crowding: increase with eccentricity, radial/tangential asymmetry, inward/outward asymmetry, horizontal/vertical asymmetry, and an upper/lower hemifield asymmetry. Furthermore, they demonstrated marked idiosyncrasies between participants.

The goal of this work is twofold: (a) to apply the CF method to measure the profile of crowding for near-foveal targets that are most relevant for saccade planning during natural, active viewing and (2) to examine the effects of this near-foveal crowding under conditions of spatial uncertainty.

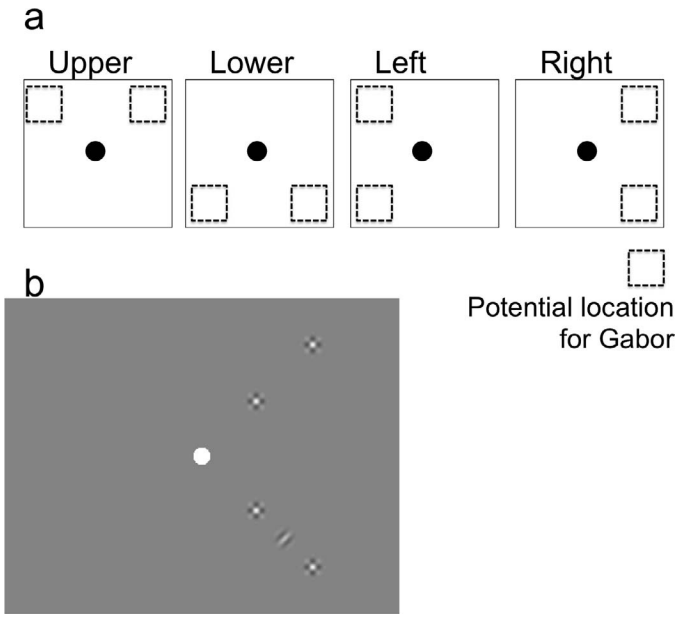

Figure 1. The stimuli. (a) The Gabor could occur with equal probabilities on either diagonal meridians in a given hemifield, here shown with dashed squares. (b) The stimuli in a trial in which Gabor was presented in the right hemifield and Gabor-flankers configuration was radial.

Materials and methods

Stimulus

Figure 1 illustrates the crowding stimuli. Participants fixated a central dot, and two sets of plaid flankers were presented in one of four possible hemifields (Figure 1a), with a Gabor target occurring randomly between one of the flanker sets. Subject to this spatial uncertainty, participants were asked to discriminate whether the upper point of the target Gabor was tilted to the left or right (Figure 1b). The target Gabor was positioned at eccentricities of 2.1, 2.8, and 3.5 vd.

The fixation point was a white disc 0.2 vd in diameter presented in the center of the screen. The target was a standard cosine phase Gabor, a sinusoidal grating of period λ in cosine phase windowed by a two-dimensional Gaussian with spatial standard deviation $\sigma = \lambda/\sqrt{2}$ in which ~1.5 cycle of the sinusoidal pattern was visible. Target contrast was fixed at 45%. This contrast is much higher than the contrast needed for the Gabor to be visible. The Gabor was tilted 45° to the left or right of the vertical meridian. The flankers were plaid masks and were made of two transparently overlaid Gabor patches. The patches were exact replicas of the target, except that one Gabor patch was rotated by 90°. Contrast of both patches was 45%, and the resulting plaid contrast was close to 90%. The

separation between the mask and the target (center-to-center) was fixed at 4 λ.

Design

The design had three within-subject factors: eccentricity (2.1, 2.8, and 3.5 vd), hemifield (upper, lower, left, and right), and crowding configuration (none, radial, tangential), for a total of 36 conditions. Each condition was blocked. Each block included 150 trials. Each condition was run three times. The order of blocked conditions was randomized.

The Gabor occurred either with or without flankers. The Gabor/flankers configuration was either radial or tangential. The stimuli occurred only on the diagonal meridian, so any radial/tangential configuration effect was not confounded with horizontal/vertical asymmetry (Feng et al., 2007; Yu, Legge, Wagoner, & Chung, 2014). The Gabor randomly appeared in one of two locations along the diagonal meridian to introduce location uncertainty and reduce effects of attention on crowding (e.g., Petrov & Meleshkevich, 2011b; Petrov, Popple, & McKee, 2007; Yeshurun & Rashal, 2010).

Apparatus

The stimuli were displayed on a gray background and viewed on a 21W ViewSonic G225f monitor. The display resolution was set to 1800 × 1440 pixels. Viewing distance was 120 cm. A pixel subtended ~0.6 min of arc. Viewing was binocular and in a dimmed room. The head was positioned with a forehead and chinrest.

Participants

Five participants (four female) with normal or corrected-to-normal visual acuity participated in the study. Two were authors. Three were naïve as to the purpose of the study. All participants were experienced in psychophysical studies. Human participants approval was granted by the Smith-Kettlewell Eye Research Institute institutional review board. The study was conducted in accordance with the tenets of the Declaration of Helsinki. Participants received compensation of $20/hour for their participation. Each participated in 8 to 10 sessions (1.5 hr each).

Procedure

Experimental procedure

Before each block of trials, participants received 10 practice trials. For each trial, participants were instructed to maintain their gaze on the fixation point and, when ready, to press the space bar to trigger the stimuli. The stimulus was shown for 150 ms to prevent eye movements. Eye movements were not recorded. Participants made an unspeeded two-alternative forced-choice response to the orientation of the Gabor, tilted left or right relative to the vertical meridian, by pressing the left or right arrow key.

Psychometric procedure

To measure crowding, we used the *CF method*, a psychometric procedure developed by Petrov and Meleshkevich (2011b) that uses a Bayesian adaptive algorithm (Kontsevich & Tyler, 1999) to adjust the Gabor size, frequency, and distance to flankers simultaneously to estimate the parameters of the psychometric function. Target size and flanker separation were defined by the spatial period of the Gabor (λ), which was varied according to the adaptive algorithm. The Gabor-flanker separation was 4λ (Petrov & McKee, 2006). The threshold was defined as $d' = 1$, which is about 84% accuracy. In the presence of flankers, the target lambda discrimination threshold increases, which means the discrimination threshold Gabor size increases. The CF is the ratio of threshold λ in the flanked versus unflanked conditions minus 1, at a given eccentricity and hemifield.

$$\text{Crowding Factor} = \frac{\text{threshold } \lambda \text{ with flankers}}{\text{threshold } \lambda} - 1$$

Thus, a CF of 0 indicated no crowding.

Results

Given that each condition was repeated three times, the threshold λ (i.e., the threshold Gabor size) for each condition and for each participant was the average of three thresholds. In the absence of flankers, as acuity declines away from the fovea, the Gabor scale needed for reliable discrimination should increase. Thus, the threshold λ should increase with eccentricity. In the presence of flankers that crowd, the CF measure should be larger than 0. First, the results for unflanked target are presented. This is followed by the results for CF in the flanked conditions.

Discriminable Gabor size (threshold λ) increases with eccentricity

We ran a 4 (hemifield) × 3 (eccentricity) repeated-measures analysis of variance (ANOVA) on λ. Figure 2 plots the results. There was no effect of hemifield, F(3,

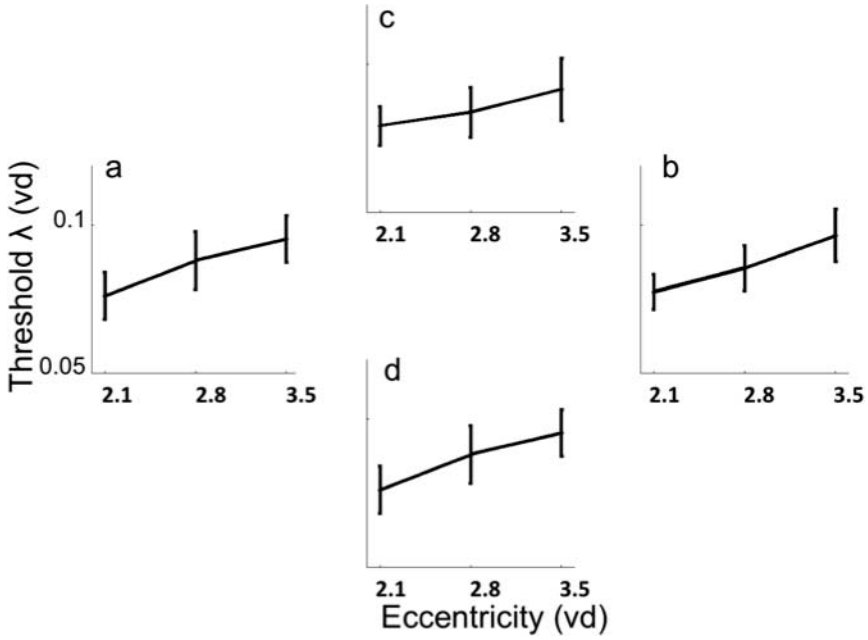

Figure 2. Average threshold λ (i.e., discriminable Gabor size) across Gabor's eccentricity for when Gabor occurred in the left (a), right (b), upper (c), or lower (d) hemifield. Error bars show one standard error of mean.

12) = 1.35, $p = 0.303$. The average threshold λ was 0.089 ($SEM = 0.008$), 0.083 ($SEM = 0.008$), 0.086 ($SEM = 0.007$), and 0.086 ($SEM = 0.007$) vd for when the stimuli were presented in the upper, lower, left, or right hemifield, respectively. There was a significant effect of eccentricity, $F(2, 8) = 45.07$, $p < 0.001$: the average spatial frequency was 0.077 ($SEM = 0.007$), 0.085 ($SEM = 0.008$), and 0.093 ($SEM = 0.008$) vd for eccentricity of 2.1, 2.8, or 3.5 vd, respectively. The linear trend of eccentricity was significant, $F(1, 4) = 66.35$, $p = 0.001$.

Crowding

A CF of 0 indicates no crowding. The radial CF was significantly larger than 0 for all participants (all p values <0.001). The tangential CF was significantly larger than 0 for all participants (all p values <0.05). We ran a 2 (Gabor-flanker configuration) × 4 (hemifield) × 3 (eccentricity) repeated-measures ANOVA on CF. There was an effect of flanker configuration, $F(1, 4) = 8.73$, $p = 0.042$: The average CF was 0.15 ($SEM = 0.04$) and 0.27 ($SEM = 0.06$) for tangential and radial configurations, respectively (see Figure 3). The eccentricity effect was marginal, $F(2, 8) = 3.49$, $p = 0.081$, but was in the expected direction: The average CF was 0.16 ($SEM = 0.03$), 0.24 ($SEM = 0.05$), and 0.24 ($SEM = 0.07$) for target eccentricity of 2.1, 2.8, or 3.5 vd, respectively. There was no effect of hemifield, $F(3, 12) = 1.37$, $p = 0.298$: The average CF was 0.25 ($SEM = 0.06$), 0.19 ($SEM = 0.03$), 0.21 ($SEM = 0.05$), and 0.21 ($SEM = 0.05$) for the upper, lower, left, or right hemifield, respectively. There was no difference between the upper and lower hemifields, $t(4) = 1.71$, $p = 0.160$.

Idiosyncrasy

Figure 4 shows the CFs in each condition for individuals in addition to the average CF. The magnitude of CF differed between participants, ranging from an average of 0.07 for S1 to an average of 0.37 for S3. The radial-tangential asymmetry holds for all participants except S2, $t(11) = -1.58$, $p = 0.07$. Figure 4 shows that for this participant, the effect of flanker configuration is reversed when the Gabor is presented in the upper hemifield but is preserved for other hemifields.

Discussion

A complete understanding of how visual information is processed requires an understanding of how crowding works during active, natural vision. The first step toward such a goal is to have a unifying method that works for *all* eccentricities. Studying crowding in parafoveal vision is important given that the next saccade target frequently falls within 5 vd of the fovea (Bahill et al., 1975). Nandy and Tjan (2012) even suggest that saccades and attention interact to shape

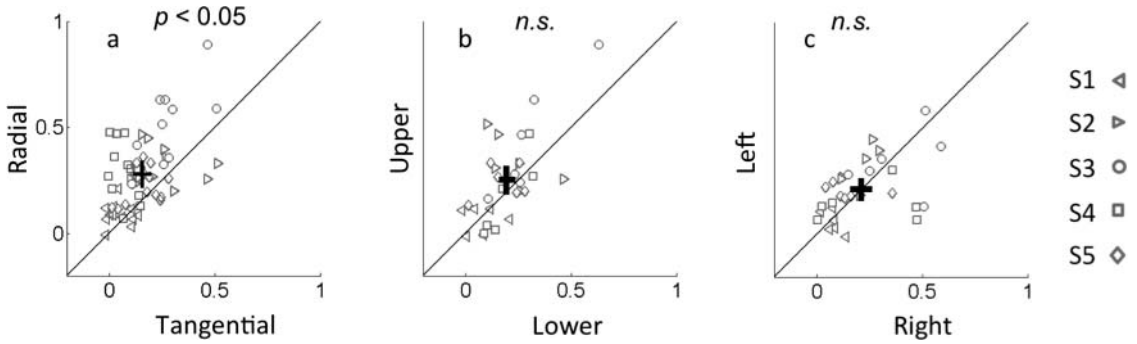

Figure 3. Average crowding factor. The average crowding factors are shown for radial versus tangential configuration (a), when the Gabor was presented in the upper versus lower hemifield (b) or the left versus right hemifield (c). Different symbols show data for different participants collapsed across different levels of the experimental design. Error bars show one standard error of mean.

the development of radially aligned crowding zones. Crowding in central vision is highly relevant to our natural perception of the world given that objects that are located within 2.6 vd of a fixation are usually recognized (Nelson & Loftus, 1980) and the functional field of view extends about 4 vd away from fixation (Henderson & Hollingworth, 1999). The CF method was capable of measuring crowding in central vision, with CFs significantly larger than 0. Furthermore, CFs were larger when target-flanker configuration was radial rather than tangential. Given that the stimuli occurred on the diagonal meridian, any radial/tangential asymmetry in crowding was not confounded with a horizontal/vertical asymmetry (Feng et al., 2007).

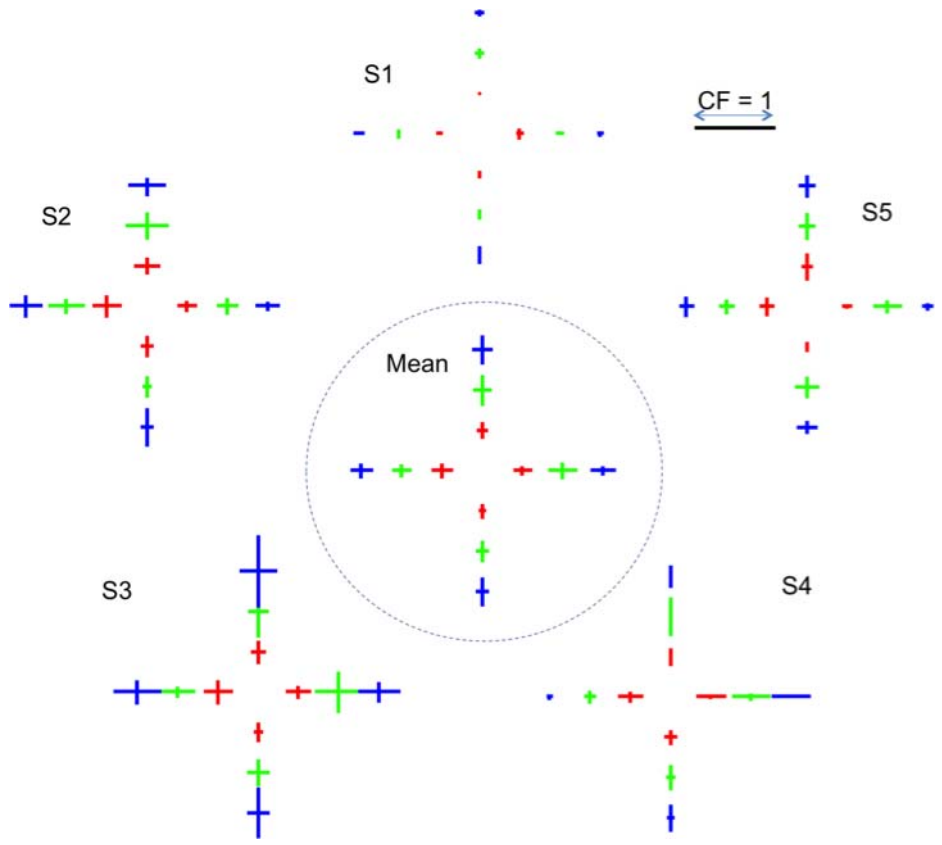

Figure 4. Individual crowding factors. The individual crowding factors (the peripheral panels) in addition to the average crowding factors (the central panel) are shown for Gabor eccentricity of 2.1 (red), 2.8 (green), and 3.5 (blue) vd. The upper, lower, left, or right side of each panel illustrates the crowding factor for when the Gabor was presented in the upper, lower, left, or right hemifield, respectively. Radial/tangential lines relative to the center of each panel show the radial/tangential crowding factor. The line in the upper right side of the figure illustrates crowding factor of 1.

Our task requires the participant to first detect the target and then identify it. It can be argued that the flanker could have masking effects at the detection stage. Although masking effects can be strong for low-contrast Gabors (Lev & Polat, 2011) and such masking effects are reported to be correlated with crowding (Doron, Spierer, & Polat, 2015; Lev & Polat, 2015), the target in our task was visible and its detection was unlikely to be affected by any masking effects of flankers.

The CFs measured in this study at 3.5 vd (mean CF = 0.24) are comparable to the range of CFs measured in the Petrov and Meleshkevich (2011a) study (CF = 0.22 at 4 vd). Crowding could have been expected to be higher in our study given the introduction of spatial uncertainty of the target; however, our stimulus duration was 50 ms longer, which may have counter-balanced this.

The CF trended upward with target eccentricity, and the increase was marginally significant. In general, crowding has been shown to increase with eccentricity, and step size likely matters. Petrov and Meleshkevich (2011a) showed a significant effect from 4 to 8 vd. The step size in this study was only 0.7°; thus, any noise (or idiosyncrasies between participants) likely masks the small corresponding effect on the CF magnitude for these eccentricities.

Petrov and Meleshkevich (2011a) showed a larger CF for the upper versus lower hemifield. The resolution of attention is finer in the lower than upper hemifield (He et al., 1996), and this may serve to uncrowd targets. Our data showed a trend but not a significant effect of upper versus lower hemifield; this marginal effect was unlikely to be due to a fixational bias or drift (Kowler & Steinman, 1979) given that the fixation target was only 0.2 vd in diameter and stimuli duration was only 150 ms. This suggests that for small eccentricities (3.5 vd and smaller), the resolution of attention needed for our task was not significantly different between the upper and lower hemifields.

Within central vision, a left/right asymmetry in crowding is reported for letters but not for symbols: Grainger et al (2010) showed that crowding was stronger in the left than right hemifield for a letter target presented 1.5 vd from fixation on the horizontal meridian but not for a symbol target. We did not find such asymmetry. It is possible that such an asymmetry is stronger along the horizontal meridian. It is also possible that such an asymmetry is specific to letter stimuli. The areas that process letter information in the brain (the visual word form area) is located in the left hemisphere (Dehaene & Cohen, 2011), and this can facilitate the processing of letters that occur in the right hemifield. Furthermore, for those writing systems in which the reader reads from left to right, the perceptual span during reading is wider (McConkie, Rayner, 1976) and the allocation of spatial attention during the course of a fixation is larger on the right than left of the gaze location (Ghahghaei, Linnell, Fischer, Dubey, & Davis, 2013). Given that crowding can be modulated by attention (e.g., Petrov & Meleshkevich, 2011b; Yeshurun & Rashal, 2010), the reader is more likely to have learned to uncrowd letters on the right side of the gaze location. Such training does not necessarily transfer to nontrained stimuli (e.g., Furmanski & Engel, 2000).

We looked at crowding along the diagonal meridians to avoid any confounding effects of horizontal/vertical asymmetry (Feng et al., 2007; Yu et al., 2014). Many studies have shown that more saccades are made along the horizontal and vertical meridians than the diagonal meridians (Brandt, 1945; Crundall & Underwood, 1998; Gilchrist & Harvey, 2006; Foulsham, Kingstone, & Underwood, 2008). Given that saccades can affect crowding (Nandy & Tjan, 2012), it is possible that crowding is weaker along the diagonal meridians than the horizontal/vertical meridians. Thus, hemifield or eccentricity effects might be stronger along the horizontal/vertical meridians.

In line with Petrov and Meleshkevich (2011a), who showed crowding idiosyncrasy in the periphery, our results showed crowding idiosyncrasy in central vision (also see Livne & Sagi, 2011). The magnitude of CF was much larger for some participants (e.g., S3) than for others (e.g., S1). Contrary to what is reported in the literature, one participant (S2) consistently showed a robust reverse radial/tangential asymmetry in the upper hemifield.

In summary, we demonstrate that the CF method can be used to measure crowding for near-foveal stimuli, allowing for a unified approach to studying visual information processing in both central and peripheral vision. Crowding in central vision is particularly important when understanding the visibility of saccade and surrounding targets during natural, active vision. Near the fovea, effects of eccentricity and hemifield are not as readily observable as in the periphery; however, radial and tangential asymmetries are clearly preserved. It is important to note that there are idiosyncratic differences between individuals in crowding that may have real consequences on vision for action.

Keywords: crowding, parafoveal vision, central vision, crowding factor method, idiosyncrasy

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