Vision Research 51 (2011) 1239–1248

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

Configuration specificity of crowding in peripheral vision

Nisha S. Yeotikar *, Sieu K. Khuu, Lisa J. Asper, Catherine M. Suttle

School of Optometry & Vision Science, University of New South Wales, Sydney, NSW 2052, Australia

ARTICLE INFO

Article history:
Received 17 August 2010
Received in revised form 8 February 2011
Available online 31 March 2011

Keywords:
Configuration
Crowding
Discrimination
Flanker
Periphery

ABSTRACT

Peripheral vision is characterized in part by poor spatial resolution and impaired visual performance, particularly when the object is surrounded by flanking elements, a phenomenon popularly known as "crowding". Crowding scales with eccentricity irrespective of the target size, both in terms of magnitude and spatial extent, which is determined by varying the target-flanker separation. However, the extent to which crowding depends upon the flanking stimuli parameters alone without separating target and flankers is poorly understood. In the present study, we investigated the effect of flanking stimulus parameters on crowding in orientation and contrast discrimination tasks using closely located "chain" lateral Gabor stimuli in order to enhance our understanding of the underlying mechanisms of crowding in peripheral vision. We found a strong configural effect on crowding in both orientation and contrast discrimination tasks, with reduced crowding when the flanker parameters enhanced the target salience and increased crowding when the flankers were perceptually grouped with the target. While in orientation discrimination crowding was dependent on eccentricity, and in contrast discrimination it was dependent on flanker contrast and eccentricity, crowding showed little dependence on the number of flankers in either task. We conclude that crowding in peripheral orientation and contrast discrimination is configuration specific, which can be reduced without alterations to the target-flanker separation and that crowding is a combination of low-level as well as high-level cortical processing.

1. Introduction

It is well known that peripheral vision is characterized by poor spatial resolution due to anatomical factors such as the arrangement of cones, populated more densely at the fovea than in the periphery and with a corresponding increase in receptive field size with eccentricity. Object recognition and identification in the periphery becomes even more difficult when presented with surrounding elements and this finding has been explained in terms of two analogous phenomena: crowding and lateral masking (Chung, Levi, & Legge, 2001; Leat, Li, & Epp, 1999; Levi, Hariharan, & Klein, 2002; Wilkinson, Wilson, & Ellemberg, 1997). Previous studies show that these phenomena differ in their underlying mechanisms and characteristics (Levi, Hariharan, et al., 2002; Pelli, Palomares, & Majaj, 2004), and that the crowding effect is profound in the periphery while lateral masking is widely reported at the fovea (Cass & Spehar, 2005a; Chung et al., 2001; Levi, Hariharan, et al., 2002; Levi, Klein, & Hariharan, 2002; Polat & Sagi, 1993).

Crowding is defined as impaired target visibility due to the presence of adjacent contours. It has been studied extensively since Korte (1923) first described reduced visibility of a target letter in the presence of neighbouring letters (Korte, 1923). Bouma (1970) defined crowding based on the critical spacing of objects (such as letters) which according to Bouma's rule, is roughly half of the viewing eccentricity. This rule has been found to apply for stimuli other than letters, such as bars, numbers and Gabor stimuli (Andriessen & Bouma, 1976; Felisbert, Solomon, & Morgan, 2005; Levi, Hariharan, et al., 2002; Pelli et al., 2004; Strasburger, Harvey, & Rentschler, 1991; Wilkinson et al., 1997). Crowding has been explained in terms of spatial pooling (Parkes, Lund, Angelucci, Solomon, & Morgan, 2001), insufficient spatial resolution of visual attention (Intriligator & Cavanagh, 2001), feature integration (Pelli et al., 2004), and target salience or pop-out (Felisbert et al., 2005; Livne & Sagi, 2007; Poder, 2006). These theories predict that apart from the critical distance between the target and flanking stimuli, the nature of flankers also plays an important role in crowding (Livne & Sagi, 2007; Saarela, Sayim, Westheimer, & Herzog, 2009).

Lateral masking is a form of *contrast masking*, which refers to the effect of lateral 'mask' stimuli on the contrast detection or discrimination of a central target such as a Gabor (Adini, Sagi, & Tsodyks, 1997; Cass & Spehar, 2005b; Polat & Sagi, 1993). Psychophysical studies show that lateral masking exerts two effects: *suppression* (elevated thresholds) and *facilitation* (reduced thresholds). The facilitation for foveal target detection by remote flankers (mask stimuli) is a consequence of the excitatory long-range horizontal connections between neurons with identical preferred orientation in V1; while suppression is a result of inhibitory

* Corresponding author.
E-mail address: n.yeotikar@unsw.edu.au (N.S. Yeotikar).

0042-6989/$ - see front matter © 2011 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2011.03.016

short-range interactions (Adini et al., 1997; Cass & Spehar, 2005a; Levi, Klein, et al., 2002; Polat & Sagi, 1993, 1994; Solomon & Morgan, 2000; Tanaka & Sagi, 1998; Woods, Nugent, & Peli, 2002; Zenger & Sagi, 1996). These spatial interactions are specific to stimulus configuration, thus being dependent on the orientation of the mask stimuli relative to the target (Polat & Sagi, 1993; Woods et al., 2002; Zenger & Sagi, 1996). Adini et al. (1997) proposed a neuronal model for lateral masking effects, which suggests that excitatory connections are stronger in collinear[1] stimuli arrangement while inhibitory connections are stronger in parallel[2] stimuli arrangement, and that increasing the number of mask stimuli improves the strength and range of inhibitory connections thereby increasing the suppression. Facilitatory and suppressive lateral interaction effects of this kind were confirmed in single-cell recordings from the primary visual cortex (Kapadia, Ito, Gilbert, & Westheimer, 1995; Polat, Mizobe, Pettet, Kasamatsu, & Norcia, 1998; Polat & Norcia, 1996). Therefore unlike crowding, lateral masking cannot only mask but also facilitate target detection, depending on the target-flanker distance and stimulus configuration.

It is well known that similar to lateral masking, crowding is also orientation specific (Andriessen & Bouma, 1976; Livne & Sagi, 2007, 2010) and depends on the distance between target and flankers, which varies with eccentricity and is generally known as the spatial extent of crowding (Chung, Legge, & Tjan, 2002; Hariharan, Levi, & Klein, 2005; Levi, Hariharan, et al., 2002; Livne & Sagi, 2007; Pelli et al., 2004; Toet & Levi, 1992). Therefore, whether 'crowding' and 'lateral masking' are two sides of a coin and/or share the same underlying mechanism, is still ambiguous (Chung et al., 2001; Levi, Hariharan, et al., 2002, Levi, Klein, et al., 2002; Parkes et al., 2001; Wilkinson et al., 1997). A widely shared view is that in crowding, information about the target is spatially pooled with that of the surrounding flankers resulting in increased target uncertainty; whilst in masking, the flankers inhibit (mask) the target signals and thus the information from the target is partially lost rendering it less visible (Parkes et al., 2001). However, in both phenomena, the target-flanker separation is a confounding factor in assessing the impact of stimulus parameters such as target and/or flanker contrast, orientation, spatial frequency, phase and colour in crowding reduction or facilitation (Chung et al., 2001; Felisbert et al., 2005; Kooi, Toet, Tripathy, & Levi, 1994; Livne & Sagi, 2007; Woods et al., 2002). In order to understand the role of such stimulus parameters in peripheral vision, the target and flankers must be located at a fixed distance. Thus we were interested in studying the effect of flanking stimulus parameters on threshold elevation using closely located target and flankers.

Crowding has been thoroughly investigated in the case of letter identification (e.g., (Bouma, 1970; Chung et al., 2001; Pelli et al., 2004; Toet & Levi, 1992) and to some extent in orientation discrimination (e.g., (Andriessen & Bouma, 1976; Felisbert et al., 2005; Livne & Sagi, 2010), but rarely studied and demonstrated in contrast detection (Levi, Klein, et al., 2002; Poder, 2008) and discrimination (Levi & Carney, 2011; Saarela et al., 2009). Orientation discrimination acts as a key function for tasks such as contour integration, which involve linking different closely located segments based on their local orientation; while contrast discrimination is a basic function to discriminate an object from the background or identify the difference between two closely located objects. Crowding is considered to be a high level phenomenon and therefore thought to be restricted to tasks which involve 'identification', whereas masking is understood to occur in lower level tasks such as 'detection' and 'discrimination' (Levi, Hariharan, et al., 2002; Livne & Sagi, 2007; Pelli et al., 2004). 'Object identification' is deemed "high level" as it is thought to engage processing in cortical areas beyond V1 (Desimone & Schein, 1987; Desimone, Schein, Moran, & Ungerleider, 1985; Motter, 1994a, 1994b), whereas neurophysiological studies provide evidence for tasks such as contrast and orientation detection and discrimination to be mediated largely by V1 (Hubel & Wiesel, 1968; Kapadia et al., 1995). Thus it remains unclear whether visual crowding is a phenomenon observed only in high-level tasks (such as those requiring stimulus feature integration) or whether it is also observed in basic judgements of form.

Recent studies have partially addressed this question by demonstrating that crowding does occur in detection and coarse discrimination (Levi & Carney, 2011; Poder, 2008; Saarela et al., 2009), but is dependent on the number of flankers (Poder, 2008). A study by van den Berg, Roerdink, and Cornelissen (2007) showed that crowding is a general phenomenon which is affected by feature dimensions such as size, hue and saturation apart from orientation (van den Berg et al., 2007). These findings indicate that crowding and lateral masking might not be differentiated on the basis of visual tasks. Henceforth, in the present study, we refer to the "lateral masking effect" (threshold elevation or suppression due to adjacent flankers) as crowding.

The spatial pooling hypothesis describes crowding as a result of (spatial) averaging of target and flanker information (Parkes et al., 2001). According to this theory, strong crowding is obtained when the target and flankers are perceived as a textural whole because the target information is pooled or combined with flanker information and then averaged by the relatively large receptive fields found in the periphery (Liu, Jiang, Sun, & He, 2009). On the other hand, when target and flankers are dissimilar, they may be processed separately reducing the likelihood of integrating their signals and thus facilitating target detection and identification (Wilkinson et al., 1997). Along with the neural correlates, previous studies also provide various perceptual explanations for crowding. A process that leads to the target pop-out when it is surrounded by a group of distracters that are different from the target is referred to as "target salience". This phenomenon was demonstrated by Kooi et al. (1994), who showed that crowding decreased when flanking stimuli were of different contrast, binocular disparity, shape, or colour relative to the target. They explained crowding as a consequence of "compulsory grouping" of similar shapes (target and flankers) by the visual system. Grouping of this kind has been shown to affect target visibility in positional discrimination at the fovea and orientation and contrast discrimination in the periphery by varying size, location and number of flankers (Malania, Herzog, & Westheimer, 2007; Saarela et al., 2009).

The purpose of the present study was to investigate the role of flanker parameters in crowding in peripheral orientation and contrast discrimination tasks using closely located "chain" lateral Gabor stimuli in order to enhance understanding of the mechanisms underpinning crowding in peripheral vision. This type of stimulus has been used previously for foveal contrast detection and discrimination but not for orientation discrimination or contrast discrimination in the periphery. Flanking stimulus manipulations such as configuration, contrast, number, and eccentricity were incorporated without variation in the distance between target and flankers to ensure that the target-flanker separation did not affect the results.

We found a strong configural effect on crowding in both orientation and contrast discrimination tasks, with dependence on the orientation similarity between target and flanking stimuli. Crowding in the two tasks showed dependencies on different flanker parameters. Our findings suggest that this configuration-specific crowding can be reduced by making simple changes to flanker parameters, which allow the target to pop-out in chain-lateral Gabor stimuli.

[1] A collinear configuration is obtained when the local and global orientations (axis of stimuli) of target and flankers are identical.

[2] A parallel configuration is obtained when the local orientation of target and flankers is identical, but is orthogonal to the global orientation (axis of stimuli).