Vision Research 102 (2014) 11–18

Contents lists available at ScienceDirect

Vision Research

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

Binocular capture: The role of non-linear position mechanisms

Avesh Raghunandan *, Jason Andrus

Michigan College of Optometry, Ferris State University, Big Rapids, MI 49307, USA

A R T I C L E I N F O

Article history:
Received 21 November 2013
Received in revised form 18 June 2014
Available online 17 July 2014

Keywords:
Binocular capture
Visual direction
Stereopsis
Vernier acuity

A B S T R A C T

When monocular Vernier targets are presented with binocular disparate elements, an increase in vertical separation elevates alignment thresholds and also shifts its perceived visual direction towards the visual direction of the binocular disparate surround. This observation has been termed binocular capture. There is increasing evidence that this shift in the visual direction of the monocular target may be related to the type of position encoding mechanism involved in processing the relative position signal. This study investigated the interaction between capture magnitude and vertical separation for stimulus conditions that favored the recruitment of linear or non-linear position encoding mechanisms. Relative alignment thresholds and bias were measured for a pair of vertically separated (8′, 30′, 60′, 120′) monocular Gabor gratings (1, 2, 4 and 8 cpd). Grating stimuli were constructed to constrain relative alignment judgments to the carrier grating (CO) or to the envelope (EO). Relative alignment thresholds and bias were also measured for a pair of vertically separated monocular Gabor gratings comprising a 1 cpd vertical square wave grating (SQ) or a 1 cpd missing fundamental grating (MF). Capture magnitudes were significantly larger across vertical separation and varied proportionally with relative alignment threshold for the EO and MF conditions. This was not evident with the CO and SQ conditions. The stark difference in capture magnitudes between the stimuli conditions suggest that the increase in capture magnitude observed with increasing vertical separation is intimately related to the transition from a “capture-immune” first-order spatial filter mechanism to a “capture-vulnerable” non-linear/feature-based position encoding mechanism.

1. Introduction

During natural binocular viewing, certain viewing conditions can create a situation in which a target is visible to one eye while surrounding targets are viewed binocularly. Such viewing situations often arise near occluding surfaces. Under such conditions it was assumed that the perceived visual direction of the monocular target follows the predictions of the Wells–Herings laws of visual direction (Hering, 1879; Howard, 2002), i.e. the oculocentric direction of a monocular target transfers unaltered to the cyclopean eye, and its perceived visual direction will be independent of the perceived visual direction of surrounding binocular targets. However, there have been several reports that this is not the case (Erkelens, Muijs, & Van Ee, 1996; Hariharan-Vilupuru & Bedell, 2009; Raghunandan, Anderson, & Saladin, 2009; Shimono et al., 1998, 2005; Shimono & Wade, 2002; Raghunandan, 2011; Van Ee, Banks, & Backus, 1999; Van Ee & Erkelens, 2000). It has been shown that monocular target localization errors (relative to Hering, 1879 prediction) occur when their locations are close to binocular contours, and the magnitude of the mislocalization error depends on the proximity of the monocular target to the binocular contour (Erkelens & Van Ee, 1997a; Shimono et al., 2005; Van Ee, Banks, & Backus, 1999).

The magnitude and direction of the localization error of the monocular target also varied systematically with the magnitude and sign of the relative disparity of the binocular surround (Hariharan-Vilupuru & Bedell, 2009; Shimono & Wade, 2002; Shimono et al., 2005). This observation has been termed binocular capture (Erkelens & Van Ee, 1997a, 1997b), because it seems as though the visual direction of the monocular target is “captured” by the cyclopean visual direction of immediately surrounding disparate targets. It has also been reported that the magnitude of the localization error (or capture) increases if the vertical separation between the monocular targets increases (Hariharan-Vilupuru & Bedell, 2009; Raghunandan, 2011; Raghunandan, Anderson, & Saladin, 2009). This last result was particularly interesting because subsequent reports have shown a systematic interaction between the spatial frequency composition of the monocular target and the separation at which the localization errors become significant (Raghunandan, 2011; Raghunandan, Anderson, & Saladin, 2009).

* Corresponding author. Address: Michigan College of Optometry, Ferris State University, 1124 S State Street, Big Rapids, MI 49307, USA.

E-mail address: raghuna@ferris.edu (A. Raghunandan).

http://dx.doi.org/10.1016/j.visres.2014.06.007
0042-6989/

This critical separation for spatial frequency ribbon targets was approximately equivalent to 1 period width of its carrier spatial frequency (Raghunandan, 2011; Raghunandan, Anderson, & Saladin, 2009).

The latter observation suggests that the vulnerability of the monocular target to capture of its visual direction by surrounding disparate targets may depend significantly on the underlying mechanisms processing the position of the monocular target. Specifically, it has been reported that in the case of Vernier alignment tasks there occurs a transition in the position encoding mechanisms from a first-order spatial frequency selective mechanism to a feature based (non-linear) mechanism as the vertical separation between the targets increased (Levi & Waugh, 1996; Mussap & Levi, 1997; Wang & Levi, 1994; Waugh & Levi, 1995). Therefore, given the similar behavior displayed by both Vernier alignment thresholds and capture magnitude with increasing separation, it raises the possibility that perhaps monocular targets are more vulnerable to capture when target separation favors processing by a feature-based position mechanism. Indeed, Raghunandan (2011) have shown that monocular Vernier targets with mismatched spatial frequency presented within a random dot depth stereogram, were significantly more vulnerable to capture compared to matched spatial frequency conditions for the same vertical separation. However, the author also reported a strong correlation between the positional uncertainty of the monocular target and the magnitude of capture. Given that positional uncertainty of a Vernier target increases with vertical separation, it raises the question whether the vulnerability to capture is due to a shift in the position-encoding mechanism or simply due to an increasing dependence on surround visual direction as the relative alignment Vernier cue becomes unreliable, independent of whether a shift in localizing mechanism has occurred.

In the present study the authors attempted to investigate the link between the emergence of binocular capture and the underlying position-encoding mechanism by employing stimuli that have been shown to selectively tap into linear spatial filter based position mechanisms or non-linear position mechanisms. In the first experiment capture magnitude was measured for increasing vertical separations for a monocular pair of Gabor targets in which the positional offset was defined either by the carrier or the envelope. The former stimulus design has been postulated to tap primarily into linear spatial filter based mechanisms especially at small separations (Levi & Waugh, 1996; Mussap & Levi, 1997; Wang & Levi, 1994; Waugh & Levi, 1995), while the latter stimulus design is consistent with the recruitment of non-linear position-based mechanisms (Hess & Holliday, 1992; Kooi, De Valois, & Switkes, 1991; Toet & Koenderink, 1998). A second experiment was conducted in which the change in capture magnitude was measured for increasing vertical separations in a 1 cpd missing fundamental (MF) grating and a 1 cpd square wave (SQ) grating. This stimulus design was employed because of the unique characteristic of the MF grating. The scalloped bars of the MF grating represents a feature that has the periodicity of the fundamental spatial frequency (1 cpd), even though it has no Fourier energy at the fundamental frequency. The authors were interested in quantifying the differences in capture magnitude between the MF and SQ conditions, specifically for separations at which the harmonics of the MF grating were incapable of mediating positional judgments. These vertical separations were inferred from the results of the first experiment. Based upon the postulations of previous studies (Georgeson & Shackleton, 1992), it was reasoned that positional offsets are processed by a non-linear/feature-based mechanism at these vertical separations.

The results of the first experiment showed that capture magnitude was indeed larger when position judgments are mediated by the envelope of the Gabor, however, relative alignment thresholds were also consistently larger for this condition. The 1 cpd SQ grating failed to display significant capture magnitude with increasing vertical separation, however, capture magnitude increased with vertical separation for the MF grating, specifically for separations at which its harmonics were incapable of providing a reliable position cue. Furthermore, capture magnitude for the MF grating co-varied with relative alignment thresholds, however, the SQ grating failed to show any change in capture magnitude for comparable changes in relative alignment threshold.

2. General methods and stimuli

2.1. Stimuli

All stimuli were programmed using Matlab™ and displayed on a linearized G4 17″ Apple Studio Display CRT monitor at a frame refresh rate of 124 Hz (period ≈ 8.044 ms) using the Psychophysics Toolbox option (Brainard, 1997; Pelli, 1997). The frame refresh rate was verified using a photo-detector and Tektronix oscilloscope. The stimuli were viewed through a front surface mirror haploscope placed at an optical distance of 138 cm (including the 12 cm optical path length added by the mirrors). The angular subtense of each pixel was 1 arcmin at the test distance. Horizontal offsets of the monocular Gabor targets of less than a single pixel width were accomplished by sub-pixel resolution (Westheimer & McKee, 1977).

2.1.1. Binocular stimulus

The binocular target comprised two 4.2 × 3.2 deg rectangular random dot stereograms (RDS) presented with a depth edge corresponding to 10 arcmin of horizontal relative disparity. Dot size was 1 arcmin at the viewing distance, and was presented as 8-bit grayscale dots with a dot density of 60 dots per degree. The vertical separation between the upper and lower rectangles presented to each eye was separated by a 4 arcmin wide gray strip (42 cd m^{-2}). The upper rectangle was presented with either crossed or uncrossed disparity relative to the bottom rectangle which was always presented with zero relative disparity (with respect to the surrounding aperture) thereby producing two depth sign conditions viz. Top near and Top far. Relative disparity was produced by equal horizontal displacement of the random dot array comprising the rectangular aperture of each eye's half image, i.e. the borders of the rectangular aperture remained aligned while the random dot array was horizontally displaced by equal amounts and in opposite directions to produce the stereogram with crossed or uncrossed disparity.

2.1.2. Monocular stimulus

2.1.2.1. Experiment 1a and 1b. The monocular stimuli comprised a pair of vertically separated Gabor targets (Fig. 1A and B) presented within a 4.2 × 3.2 deg gray aperture of mean luminance (42 cd m^{-2}). The monocular stimuli (vertically separated Gabors in one eye and mean-luminance field in the other eye) were perceived as superimposed on the RDS by interleaving successive frames. The Gabor targets had a horizontal sigma of 30 arcmin and a vertical extent of 66 arcmin. Gabor targets were windowed horizontally only. The carrier grating comprised either vertical (Experiment 1a: CO condition – Fig. 1A) or horizontal (Experiment 1b: EO condition – Fig. 1B) sinusoidal gratings presented with a peak contrast of 0.5 due to the temporal interleaving of the monocular and binocular stimuli. The carrier spatial frequencies were 1, 2, 4 and 8 cpd. In the case of the CO (carrier-only) condition, horizontal offsets between the top and bottom Gabors were produced by phase shifts of the top carrier grating relative to the bottom grating. The Gabor envelope was not displaced. However, in the EO (envelope only)