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Mechanisms underlying global stereopsis in fovea and periphery

Nirel Witz, Robert F. Hess *

McGill Vision Research, Dept. Ophthalmology, McGill University, Montreal, Quebec, Canada

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ABSTRACT

To better understand the pooling properties underlying global stereopsis we examined the relationship between carrier luminance spatial frequency and modulator disparity spatial frequency. Thresholds for detecting global sinusoidal disparity corrugations of spatially band-pass noise were measured as a function of modulator disparity spatial frequency for both centrally and peripherally located stimuli using a standard 2-IFC task. We found a characteristic relationship that depended on modulator disparity spatial frequency. At high modulator disparity spatial frequencies (>1 c/d), there is an optimal ratio of around 2.6, whereas at low modulator disparity spatial frequencies, there is an optimal absolute carrier luminance spatial frequency (i.e., 3 c/d). In the periphery, vision is restricted to modulator disparity spatial frequencies below 1 c/d and, as a consequence, following the above rule, there is an optimum absolute carrier luminance spatial frequency that reduces in spatial frequency with increasing eccentricity. This finding is consistent with there being more than one channel processing global stereo that is subsequently confirmed using a 2 × 2 AFC detection/discrimination paradigm. Furthermore, because of the different carrier/modulator relationships in central and peripheral vision, peripheral global stereo cannot be simply related to central global stereo by a scaling factor and thus cannot be simply due to cortical magnification, as originally thought.

1. Introduction

The visual system has a number of stereoscopic mechanisms, some involving local (Ogle, 1964) processing and others involving global (Tyler, 1974) processing. In general, global stereopsis is thought to involve a two-stage serial process, the first processing local absolute and relative disparity in early visual brain areas (V1–V2) by disparity-selective, binocular cells with localized receptive fields (Barlow, Blakemore, & Pettigrew, 1967; Cumming & Read, 2005; Ohzawa, De Angeles, & Freeman, 1996; Parker & Cumming, 2001; Pettigrew, Nikara, & Bishop, 1968; Qian, 1994) and the second, processing global corrugations of disparity by cells with much larger receptive fields in higher visual brain areas that involve the integration of local stereoscopic information over large spatial distances. It is unclear what the relationship is between the luminance spatial channels comprising the first stage of local disparity encoding and the spatial channels comprising the second stage of global disparity encoding. For example, *do all first stage detectors input to all second stage detectors or is there a specific rule that describes the pooling of local disparity information by global disparity mechanisms? Is there an optimal ratio between the carrier frequency and the modulation frequency? Does such a pooling rule, if it exists, apply to the whole visual field or does it vary with retinal eccentricity?*

In this paper, we use the term *carrier luminance spatial frequency* to mean the spatial frequency of a luminance defined 2-D noise pattern. The term *modulator disparity spatial frequency* is defined as the spatial frequency of the modulation of the carrier's disparity. As well, the term *disparity corrugation* also known as *disparity modulation* refers to the amplitude of the modulation of the carrier's disparity.

Three previous studies have sought to determine the relationship between carrier luminance spatial frequency and modulator disparity spatial frequency for central vision. In the first study by Pulliam (1981), thresholds for detecting vertical disparity corrugations were measured using disparity-modulated sine-wave gratings. Based on the results, Pulliam (1981) proposed that low spatial frequency luminance channels subserved low spatial frequency disparity channels and high spatial frequency luminance channels subserved high spatial frequency disparity channels. This linkage is consistent with there being a single ratio describing the relationship between carrier luminance spatial frequency and modulator disparity spatial frequency.

In a second study by Lee and Rogers (1997), thresholds for detecting horizontal disparity corrugations were measured using 2-D narrowband filtered random dot stereograms. Results revealed that disparity threshold functions measured across a range of luminance spatial frequencies (1–8 c/d) and at four disparity modulation spatial frequencies (0.125–1 c/d) exhibited a band-pass characteristic with peak luminance sensitivity at 4 c/d. The authors

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* Corresponding author. Fax: +1 5148431691.
E-mail address: robert.hess@mcgill.ca (R.F. Hess).

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concluded that carrier luminance spatial frequency and modulator disparity spatial frequency are largely independent dimensions and thus only the absolute carrier luminance spatial frequency around 4 c/d was important for stereo.

In the third study by Hess, Kingdom, and Ziegler (1999), thresholds for detecting near-vertical disparity corrugations were measured using randomly positioned Gabor micropatterns, in which subjects had to make a foveal global disparity orientation judgment. Disparity thresholds were measured as a function of disparity spatial frequency (0.01–0.3 c/d) across a range of luminance spatial frequencies. Results revealed that disparity thresholds did not depend on luminance spatial frequency at low disparity spatial frequencies. However, at mid disparity spatial frequencies there was a dependence on luminance spatial frequency. More specifically, the higher the luminance spatial frequency, the lower the disparity threshold. These results led the authors to conclude, contrary to Lee and Rogers (1997), that carrier luminance spatial frequency and modulator disparity spatial frequency are dependent dimensions at least in the mid to high modulator disparity spatial frequency range.

Since the processing of global disparities is a two-stage process, it is fundamental to understand the linkage between the spatial properties of 1st and 2nd stage detectors. Owing to the conflicting nature of the above results, in the present study we have decided to re-examine the relationship between carrier luminance spatial frequency and modulator disparity spatial frequency in the fovea using random-dot stereograms. We have also set out to examine whether this relationship is different in central and peripheral parts of the visual field, an issue on which there is no previous information. To address these two issues, we measured global disparity thresholds to vertically oriented sinusoidal disparity corrugations of spatially band-pass noise whose contrast was set to be a constant factor above detection threshold for all conditions. This allowed us to factor out detectability changes that are known to occur across luminance spatial scale (Campbell & Robson, 1968) and eccentricity (Robson & Graham, 1981). We assessed the relationship between the luminance spatial frequency of the noise carrier and the disparity spatial frequency of the envelope modulation for central vision and at different peripheral loci. This enabled us to produce global disparity sensitivity functions (DSFs) measured under optimal conditions of the carrier, ensuring that the carriers were all equi-detectable, and taking into account the effects of spatial summation. With this information we were able to address two related issues. Firstly, how is peripheral global stereo related to central global stereo. One recent suggestion is that central and peripheral global stereo are simply related to one another by a scale factor that could have its explanation in the amount of cortex devoted to central vs. peripheral function (Prince & Rogers, 1998)? Secondly, is there just a single underlying global disparity channel for vertically oriented global disparity stimuli? Global processing of horizontal disparity could in principle be processed by a single or multiple channels. A recent proposal is that there is a single underlying very broad channel for vertical but not horizontally modulated corrugations (Serrano-Pedraza & Read, 2010). This single channel proposal would have consequences for the relationship between carrier and modulator spatial frequency alluded to above. In this case one would expect the same relationship regardless of eccentricity.

2. Methods

2.1. Apparatus

Psykinematix software v1.3.2 was used to generate and present all stimuli as well as record responses. A Macintosh computer running the Mac OS X version 10.6.8 ran the software while stimuli were presented on a 20-in. Dell Trinitron CRT monitor (40.5 × 30.5 cm). The display had a spatial resolution of 1024 × 768 pixels and the contrast resolution was 10.8 bits using the Psykinematix bit-stealing algorithm. The monitor was geometrically calibrated and gamma corrected using an Eye-One photometer (X-Rite i1 Display 2) using Psykinematix software v1.3.2. Disparity was generated by monocular displacements computed at sub-pixel resolution. Dichoptic presentation of the left and right eye images was achieved using CrystalEyes liquid crystal shutter glasses (RealD CrystalEyes 4). The monitor refresh rate was 120 Hz, so that each eye's image was presented at 60 Hz.

2.2. Stimuli

For experiments measuring disparity thresholds in the fovea, a Gabor (modulator) disparity corrugation stimulus was used. The foveal stimulus consisted of circularly windowed, vertical disparity corrugations of a band-pass luminance carrier. Peak luminance spatial frequencies of the carrier were from 0.5 to 10 c/d. The modulator disparity spatial frequencies tested were 0.25, 0.35, 0.5, 1, 2 and 4 c/d. However, cases where the carrier luminance spatial frequency was less than two times the modulator disparity spatial frequency were excluded because of sampling considerations.

The foveal Gabor corrugation stimuli for the left and right eyes were generated by multiplying a luminance noise carrier by a 1-D vertical sinusoidal modulator (or a 1-D squarewave modulator for the results displayed in Fig. 4C). The carrier consisted of narrowband (1 octave, half amplitude, full bandwidth) filtered isotropic noise set to 7 times its contrast detection threshold under all conditions. The global disparity sinusoidal modulation was contained within a 2-D Gaussian spatial envelope (sigma was either 9° (see Fig. 4A–C) or 2.2 cycles (see Fig. 4D) in different experiments) and presented abruptly in time (500 ms). While this type of stimulus generation has the potential of producing visible monocular stimulus artifacts due to local image shearing, we ensured that thresholds were determined by disparity rather than any purely monocular displacement artefact by also measuring stimulus detectability without the stereo goggles under binocular viewing. These thresholds were always much higher than those obtained with the dichoptic presentation using the stereo goggles. The two thresholds were closest at 10 c/d, the highest carrier luminance spatial frequency used. Even under these conditions disparity provided the lower threshold.

The peripheral stimulus consisted of an annular windowed, angular disparity modulation (a sinewave defined in polar coordinates) of a band-pass luminance carrier. We tested eccentricities of 2.5°, 5°, 15° and 30° with the spatial sigma of the Gaussian annulus envelope in degrees being 0.25°, 0.5°, 1.5° and 3°, respectively. Thus the stimulus was an annulus whose width was scaled linearly with eccentricity. This was an arbitrary scaling as a compromise between, on the one hand the possibility that peripheral sensitivity could be disadvantaged by having a fixed annular width and on the other, the necessity of localizing the stimulus in eccentricity. It did not restrict the number of cycles of low disparity modulations as the modulations were orthogonal to the width. Peak carrier luminance spatial frequencies tested were from 0.75 to 10 c/d (filtered white noise with bandwidths of 1 octave). The contrast of the carrier was always set to be 7 times its contrast detection threshold. The modulator disparity spatial frequencies tested were 2, 4, 8, 16 and 32 cycles per circumference. However, cases where the carrier luminance spatial frequency was less than two times the modulator disparity spatial frequency were excluded.

2.3. Observers

Six observers participated in the foveal experiment of which four were naïve to the purpose of the experiments. Three observers