Vision Research 123 (2016) 41–45

Contents lists available at ScienceDirect

Vision Research

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

# Size matters: Perceived depth magnitude varies with stimulus height

Inna Tsirlin [a,c], Laurie M. Wilcox [a,*], Robert S. Allison [b]

[a] Centre for Vision Research, Department of Psychology, York University, 4700 Keele St., Toronto, Ontario, Canada
[b] Centre for Vision Research, Department of Electrical Engineering and Computer Science, York University, 4700 Keele St., Toronto, Ontario, Canada
[c] Eye Movement and Neuroscience Laboratory, The Hospital for Sick Children, 555 University Avenue, Toronto, Ontario, Canada

## ARTICLE INFO

*Article history:*
Received 10 June 2015
Received in revised form 9 April 2016
Accepted 10 April 2016
Available online 19 May 2016

*Keywords:*
Stereopsis
Depth perception
Disparity
Size–disparity correlation
Energy model

## ABSTRACT

Both the upper and lower disparity limits for stereopsis vary with the size of the targets. Recently, Tsirlin, Wilcox, and Allison (2012) suggested that perceived depth magnitude from stereopsis might also depend on the vertical extent of a stimulus. To test this hypothesis we compared apparent depth in small discs to depth in long bars with equivalent width and disparity. We used three estimation techniques: a virtual ruler, a touch-sensor (for haptic estimates) and a disparity probe. We found that depth estimates were significantly larger for the bar stimuli than for the disc stimuli for all methods of estimation and different configurations. In a second experiment, we measured perceived depth as a function of the height of the bar and the radius of the disc. Perceived depth increased with increasing bar height and disc radius suggesting that disparity is integrated along the vertical edges. We discuss size–disparity correlation and inter-neural excitatory connections as potential mechanisms that could account for these results.

## 1. Introduction

It is well-documented that several aspects of stereoscopic depth perception vary with the scale of the stimulus. Schor and Badcock (1985) and Heckmann and Schor (1989) showed that stereoacuity decreased with decreasing spatial frequency of difference of Gaussians or sinusoidal luminance gratings. Using bars of different widths and the same height, Richards and Kaye (1974) showed that the maximum disparity that resulted in depth perception, and the disparity that produced the greatest depth percept, increased with increasing line width. In a related study, Tyler and Julesz (1980) used planar RDS displays composed of a central target in front of a larger background. They found that the maximum disparity that supported stereopsis increased as the central rectangle increased in size (both width and height).

In other studies, Tyler (1973, 1975) used vertical line stereograms with sinusoidal and square wave depth modulations of varying frequency to show that larger stereoscopic thresholds, fusional limits and upper disparity limits for stereopsis were obtained for lower frequency modulations compared to higher frequency modulations. He also found that for a particular spatial frequency, increasing the number of cycles visible to the observer, and thus the line height, increased the upper disparity limit. Tyler proposed that these effects were due to the existence of a size–disparity correlation, where neurons tuned to large scales encode large disparities and neurons tuned to small scales encode small disparities. According to this account, large disparity detectors require large objects (both in height and width) to fire optimally, but small disparity detectors respond best to fine features. As a result, both the upper disparity limits and discrimination thresholds are lower for smaller objects. Other support for the relationship between disparity selectivity and stimulus size was provided by Felton, Richards, and Smith (1972) who adapted observers to sinusoidal gratings presented with disparity relative to a fixation stimulus. Adaptation to large disparities occurred only for low-frequency gratings (large component width), while adaptation to small disparities occurred only for high-frequency gratings (small component width). Smallman and MacLeod (1994) reported that this size–disparity correlation was also evident at contrast threshold for filtered RDS stimuli, even when vergence was carefully monitored.

In a recent article, Tsirlin, Wilcox, and Allison (2012) reported a new relationship between depth from stereopsis and object size. They found that the *magnitude* of perceived depth between a filled rectangle and a small disc appeared smaller than the depth between the rectangle and a long bar, even when both the disc and the bar had the same relative disparity and width. To our knowledge, this was the first demonstration that object height can affect suprathreshold depth percepts for objects with equivalent disparity.

---

* Corresponding author.
*E-mail address:* inna.tsirlin@sickkids.ca (I. Tsirlin).

http://dx.doi.org/10.1016/j.visres.2016.04.006
0042-6989/

The aim of the current work is twofold. In Experiment 1, we evaluate the generalizability of Tsirlin et al.'s results to other stimulus configurations and depth estimation methods. In Experiment 2, we assess whether the increase in perceived depth with increasing object height depends on the spatial integration of disparity signals. We find that perceived depth depends on stimulus height regardless of the configuration and the depth estimation method, and that disparity is integrated along the vertical contours of the objects. Finally, we suggest size–disparity correlation and excitatory inter-neural connections as potential mechanisms underlying the integration of disparity signals along vertical stimulus edges.

## 2. Experiment 1

### 2.1. Methods

#### 2.1.1. Observers

Six volunteers participated in the experiment. They all had normal (or corrected to normal) visual acuity and stereoacuity of 40 arcsec or less as assessed with the Randot stereoacuity test. All the observers, except for one (IT), were naive to the purposes of the experiment. Informed consent was obtained from each observer before the experiment. This work has been carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

#### 2.1.2. Apparatus

Stimuli were shown using a mirror stereoscope built with a pair of ViewSonic G225f CRT monitors with resolution of 1920 × 1200 pixels and refresh rate of 100 Hz. At the viewing distance of 0.6 each pixel subtended 1.46 arcmin. Stimuli were generated using Psychtoolbox package (v. 3.0.8) (Brainard, 1997) for MATLAB (v 7.4).

#### 2.1.3. Stimuli

Four types of stimuli were used (see Fig. 1):

(a) Rectangle-Bar – a rectangle with zero disparity (all disparities are specified with respect to initial fixation) next to a bar with uncrossed disparity (Fig. 1A).
(b) Rectangle-Disc – a rectangle with zero disparity next to a disc with uncrossed disparity (Fig. 1B).
(c) Two-Bars – two bars side by side, one with zero disparity and the other with uncrossed disparity (Fig. 1C).
(d) Two-Discs – two discs side by side, one with zero disparity and the other with uncrossed disparity (Fig. 1D).

The bars in all stimuli had a width of 5.8 and length of 146 arcmin and the discs had a diameter of 5.8 arcmin. The relative disparities between the pairs of objects were one of 2.9, 5.8 and 8.76 arcmin (theoretical depth of 0.56, 1.13 and 1.72 cm for an IOD of 6.5 cm). Stimuli were black on a grey background (10 cd/m$^2$). The Rectangle-Bar and the Rectangle-Disc stimuli were used by Tsirlin et al. (2012). The two new stimuli, Two-Bars and Two-Discs were used to test the generality of the Tsirlin et al. (2012) results. Prior to testing observers' interocular separation was measured using a pupilometer.

#### 2.1.4. Procedure

Observers were asked to estimate the depth (or disparity) between the two objects on the screen (rectangle and bar, rectangle and disc, two bars or two discs) using three methods of estimation:

(1) Disparity probe (DP) – a square subtending 17.5 × 17.5 arcmin was presented to the left of the stimulus objects. The square could be moved in depth in 0.7 arcmin steps using a gamepad. Observers were asked to adjust the disparity probe to the perceived depth of the object with the uncrossed disparity.
(2) Virtual ruler (VR) – a virtual vertical ruler (Tsirlin et al., 2012) was presented on the screen to the left of the zero disparity object (see Fig. 2A). The ruler consisted of a vertical line subtending 3 × 496 arcmin bisected by a horizontal line subtending 30 × 3 arcmin and another, moveable, horizontal cursor line (30 × 3 arcmin). Observers were asked to position the cursor (using the mouse) such that the distance between the bisection mark and the cursor matched the perceived depth between the two objects.
(3) Physical ruler (PR) – a purpose-built touch sensitive sensor. A rectilinear SoftPot membrane potentiometer (SpectraSymbol) was mounted to an aluminium bar. The sensor strip was 200 mm long and 7 mm wide with a total resistance of 10 kOhm. The potentiometer allowed linear measurements across the 200 mm length, with a resolution of approximately 0.2 mm. Responses were read using an analog to digital converter and a 16-bit micro controller. The recorded voltage was converted to millimetres using a MATLAB script, and calibrated prior to testing. The observers were required

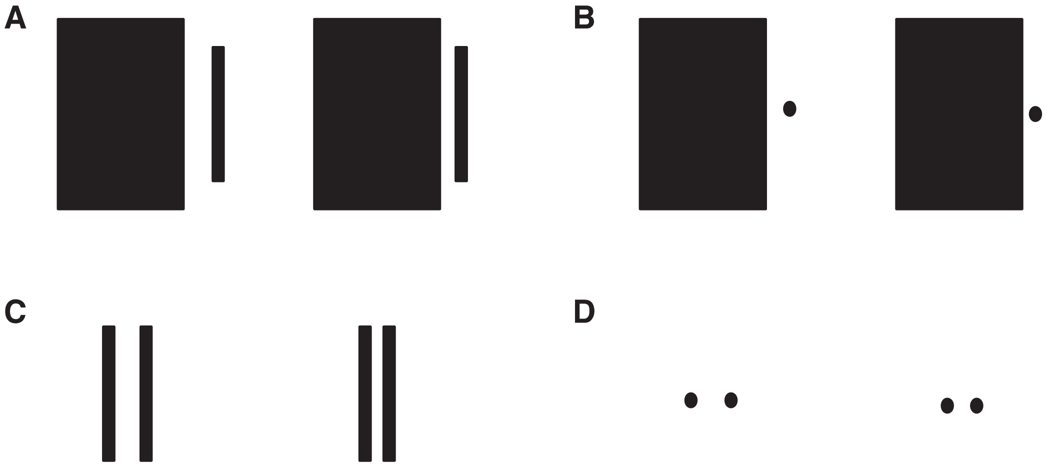

**Fig. 1.** The four types of stimuli of Experiment 1 – (A) Rectangle-Bar, (B) Rectangle-Disc, (C) Two-Bars and (D) Two-Discs. When cross-fused, the object to the right should appear further away than the object to the left. For divergent fusion the depth order is reversed.