Vision Research 124 (2016) 15–23

Contents lists available at ScienceDirect

Vision Research

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

The computation of relative numerosity, size and density

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ARTICLE INFO

Article history:
Received 14 June 2014
Received in revised form 11 December 2014
Accepted 16 December 2014
Available online 14 January 2015

Keywords:
Psychophysics
Texture
Density
Size
Numerosity

ABSTRACT

To investigate the mechanisms for the perception of relative numerosity, we used two-interval forced-choice (temporal 2AFC) to measure thresholds for area, density and numerosity differences between dot textures, and a 2×2 FC task to measure the ability of observers to distinguish changes in area from changes in density. To prevent the use of a one-dimensional size signal we used textures in which dots were scattered within irregular polygonal areas. Numerosity thresholds were similar in the area and density-varying conditions, consistent with a single numerosity mechanism. Thresholds for area and density discriminations were raised when number was held constant, consistent with numerosity thresholds being lower than those for size and density. Also, area thresholds for polygonal outlines were increased when no dots were present in the outline. However, a single numerosity mechanism cannot account for all the data, because we find that observers in randomly-interleaved size-varying and density-varying conditions are also able to discriminate between changes in size and density with a precision predicted from independently-noisy size and density channels that have similar noise to that in the putative numerosity channel. A complication, previously noted with circular shapes, is that denser textures tend to be confused with larger textures, and vice versa. This could explain why thresholds rise when density and size changes are in opposition, in the constant-number case. These findings taken together do not rule out an independent numerosity mechanism, but they are equally compatible with a flexible computation of numerosity from size and density cues.

1. Introduction

Relative numerosity discrimination has been studied experimentally in adults (Burr & Ross, 2008; Durgin, 1995, 2008; Ross & Burr, 2010) infants (Xu & Spelke, 2000), and non-human species (Brannon et al., 2001; Gallistel, 1989; Leslie, Gelman, & Gallistel, 2008), using psychophysics (Barlow, 1978), fMRI (Harvey et al., 2013; Piazza et al., 2007), and single unit physiology (Nieder, 2005). It has been suggested that there is a 'visual sense of number' (Burr & Ross, 2008) and that 'Vision senses number directly' (Ross & Burr, 2010) for large numbers of tokens. Here we attempt to discover whether there is indeed a mechanism for numerosity separate from density and size of textures. A common-used strategy for measuring relative numerosity thresholds is to scatter the tokens within a confined area, such as a circle (Burr & Ross, 2008; Durgin, 1995; Raphael, Dillenburger, & Morgan, 2013). In these circumstances, changing the number of tokens must change either the area of the pattern or the density of items. Weber fractions for numerosity are lower when the numerosity change is accompanied by a change in area (Raphael, Dillenburger, & Morgan, 2013), in agreement with other studies showing that a high-precision, one-dimensional mechanism is responsible for area discrimination of circles (Morgan, 2005; Nachmias, 2011). Therefore, experiments with circular textures may overestimate the accuracy of true numerosity discrimination. Randomly interleaving size-varying and density-varying trials (Burr & Ross, 2008; Raphael, Dillenburger, & Morgan, 2013) does not solve this problem, since observers may use whichever of the two independently noisy signals, size or density, is larger on a particular trial (Raphael, Dillenburger, & Morgan, 2013). For these reasons, we thought it desirable to repeat the experiment of Burr and Ross (2008) using stimuli with non-circular polygonal outlines (Fig. 1). We compared four conditions: (1) density-varying trials alone (2) area varying trials alone (3) interleaved area-density trials where the observers made a numerosity discrimination and (4) which is the same as condition 3, but in addition observers had to decide whether the difference was in area or in density. We expected area thresholds for random polygons to be higher than those for circles, and the

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http://dx.doi.org/10.1016/j.visres.2014.12.022
0042-6989/

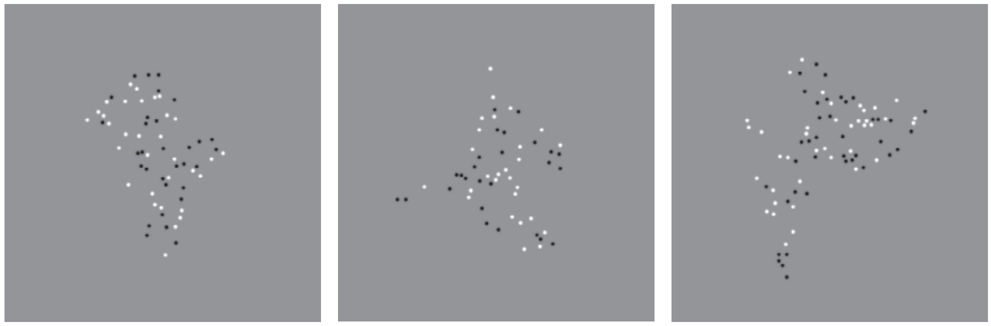

Fig. 1. Example stimuli. Left: Test stimulus of the same area as the standard and greater density. Center: Standard stimulus containing 64 dots within the standard area. Right: Test stimulus with larger area than the standard but the same density. The shapes were generated by an algorithm that randomly varied the position and number of vertices in the polygon while keeping area constant.

first question was whether this would also raise thresholds for numerosity. In additional conditions subjects discriminated changes in density or changes in size when numerosity was constant.

In signal-detection models of the data, we asked whether independently noisy area and density channels were sufficient to account for the data, or whether a separate numerosity mechanism is required. We addressed this question by comparing two-channel vs three channel fits to the combined data in all conditions.

2. Methods

2.1. Stimuli and procedure

Examples of the stimuli are shown in Fig. 1. Stimuli were presented on the LCD display of a MacBookPro laptop computer with screen dimensions 33×20.7 cm (1440×900 pixels) viewed at 0.57 m so that 1 pixel subtended a visual angle of 1.25 arcmin. The background screen luminance was 50 cd/m^2. Stimulus presentation was controlled by MATLAB and the PTB3 version of the Psychtoolbox. On each trial subjects saw consecutively two stimuli, which they were required to compare for number, density or size.

Each stimulus contained a number of fuzzy dots with a diameter of 10 arcmin and a Gaussian envelope with a space constant of 2.5 arcmin. Each dot was randomly assigned a negative (black, 0.4 cd/m^2) or positive contrast (white, 300 cd/m^2). The dots were randomly positioned within notional polygons without overlap. The irregular polygon shapes were generated by an algorithm that pseudo-randomly varied the position and number of vertices of each polygon in any trial. In all conditions the standard stimulus contained 64 dots within the standard area of 50,000 pixel, which corresponds to a circular area of 2.63° radius. An example is shown in the center panel of Fig. 1. The standard and the test stimuli were presented for 0.5 s each in random order (2AFC). Between the two intervals a gray blank screen with a central fixation cross was shown for 0.75 s. After each stimulus pair a key press was awaited while only the fixation cross was presented. The test and standard positions were separately offset from the fixation point to avoid interference by afterimages and to prevent the observer from using landmarks on the screen for size judgments. The offset was randomly selected in both horizontal and vertical direction from a uniform distribution with a width of 75 arcmin (60 pixel). The test stimulus either varied in texture size with dot density kept constant at the level of the standard (left panel of Fig. 1) or in dot density with size kept constant at 2.63 arcmin radius (right panel). The number of dots co-varied with size or density, respectively. The deviation in either texture size or density relative to the standard patch was chosen by an adaptive procedure (Watt & Andrews, 1981) in steps of 4%. The procedure was designed to obtain the 50% point (μ) and the standard deviation (σ) of the psychometric function efficiently by concentrating cue values at $\mu \pm \sigma$.

Similar to the experiment with circular structures described in Raphael et al. (2012) the following conditions and Trial Types were used. We use 'Condition' to refer to a block of trials containing the same Task and one or two Trial Types and, 'Trial Type' to refer to the kinds of trial within a block.

The 'Density Condition' consisted of blocked density varying trials where the area of the test was the same as the standard and the density of dots co-varied with the number. Observers estimated the differences in density between the test and standard patch. Similarly, the 'Size Condition' consisted of size varying trials where the density of the dots in the test was the same as in the standard, and the area was adjusted to accommodate the greater or smaller number of dots at that fixed density. Here, observers were asked to estimate the differences in texture area. In both conditions, size varying and density varying trials were presented in separate blocks and observers made a binary choice: 'denser'/'less dense' and 'larger'/'smaller'. In a modified Size Condition, the 'Outline Size Condition' only the outline of the polygon shape was shown but no dots. Here, observers compared area size of the test stimulus with the area size of the standard.

In the 'Mixed Task Condition' and in the 'Numerosity Condition' trials of size and density varying cues were randomly interleaved. In the 'Mixed Task Condition' observers were asked which kind of difference (size or density) was present, and the direction of change. In the 'Number Condition' the observers had only two keys available, to indicate which stimulus had more dots (numerosity discrimination).

Since we cannot prevent observers in the density and size conditions using numerosity as a cue (because both signals co-vary with numerosity), we introduced a further condition to estimate size ('Extended Size Condition') and density ('Extended Density Condition') changes alone. Here, we introduced a trial-type for which the number of dots was kept constant at 64 dots in each stimulus with size and density of the test varying oppositely to each other. Hence, in the Extended Size Condition in half of the trials a larger stimulus coincided with less density and in the 50% of trials a larger stimulus coincided with higher numerosity, but constant density compared to the standard. The aim of this arrangement is to prevented observers from using numerosity as a reliable cue to estimate the density or size of the texture.

An overview of all conditions is given in Table 1.

Prior to the experiments the observers were shown examples of the stimuli and were told about the relationship between density, size and number of dots in the different conditions.