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Brief article

Statistical regularities reduce perceived numerosity

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ABSTRACT

Numerical information can be perceived at multiple levels (e.g., one bird, or a flock of birds). The level of input has typically been defined by explicit grouping cues, such as contours or connecting lines. Here we examine how regularities of object co-occurrences shape numerosity perception in the absence of explicit grouping cues. Participants estimated the number of colored circles in an array. We found that estimates were lower in arrays containing colors that consistently appeared next to each other across the experiment, even though participants were not explicitly aware of the color pairs (Experiments 1a and 1b). To provide support for grouping, we introduced color duplicates and found that estimates were lower in arrays with two identical colors (Experiment 2). The underestimation could not be explained by increased attention to individual objects (Experiment 3). These results suggest that statistical regularities reduce perceived numerosity consistent with a grouping mechanism.

1. Introduction

The visual system is efficient at perceiving numerical information in the environment. For instance, we can quickly approximate the number of items (Ansari, 2008; Dehaene, Dehaene-Lambertz, & Cohen, 1998; Feigenson, Dehaene, & Spelke, 2004). Since number is a discrete measure of unitized items, what determines the unit over which number is computed? The unit of input is flexible and can involve either a discrete item (e.g., one bird), or a set of items (e.g., one flock of birds). The latter is typically determined by explicit grouping cues, such as shared features (Halberda, Mazzocco, & Feigenson, 2008; Halberda, Sires, & Feigenson, 2006), categorical memberships (Feigenson, 2008; Halberda & Feigenson, 2008), spatial arrangement (Ginsburg, 1976, 1978), and segmentation (Franconeri, Bemis, & Alvarez, 2009; He, Zhang, Zhou, & Chen, 2009).

The grouping cues not only define the level of input for enumeration, but highlight the relationships among objects, which can in turn shape numerosity perception. For instance, objects connected by lines are underestimated compared to disconnected objects (Franconeri et al., 2009; He et al., 2009). In addition to explicit grouping cues, objects can be associated in other ways. Indeed, relationships among objects are often not immediately available, but are extracted over repeated experiences. For instance, if an object always appears next to another object over multiple occasions, the joint probability between the two is 1. This reliable co-occurrence effectively associates the objects, without explicit grouping cues.

One mechanism supporting the extraction of regularities is statistical learning (Fiser & Aslin, 2001; Saffran, Aslin, & Newport, 1996; Turk-Browne, Jungé, & Scholl, 2005; Zhao, Al-Aidroos, & Turk-Browne, 2013). Statistical learning extracts probabilistic relationships between objects over space and time, generates implicit knowledge about these relationships (Aslin & Newport, 2012; Perruchet & Pacton, 2006), and allows for chunking of objects (Brady, Konkle, & Alvarez, 2009; Kirkham, Slemmer, & Johnson, 2002; Saffran et al., 1996). An important distinction between statistical learning and grouping is that the knowledge about object co-occurrences is implicit, since observers are not consciously aware of the underlying regularities (Turk-Browne, Scholl, Chun, & Johnson, 2009; Zhao et al., 2013).

Given that regularities facilitate chunking, we hypothesize that statistical learning shapes numerosity perception via implicit grouping. Specifically, exposure to object co-occurrences may lead to the unitization of objects, thus reducing the perceived numerosity. In line with past research showing that ensemble representation diminishes the perceived variability of heterogeneous stimuli (e.g., Burr & Ross, 2008; Dakin, Mareschal, & Bex, 2005; Sweeny, Haroz, & Whitney, 2013), the current study reveals how the visual system processes the complex environment and represents multiple stimuli at once.

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To seek evidence for this hypothesis, we conducted three experiments. Participants estimated the number of colored circles in arrays. Unbeknownst to them, the arrays contained color pairs containing two distinct colors (Experiments 1a and 1b). We examined whether the presence of color pairs reduced numerosity estimates. To test the grouping mechanism, we introduced color duplicates containing two identical colors, and examined if the grouping cue reduced numerosity estimates (Experiment 2). Finally, we tested an alternative explanation by introducing color pop-outs, and examined whether attention to individual objects influenced numerosity perception (Experiment 3).

2. Experiment 1a

The experiment aimed to examine whether regularities reduce numerosity estimates via implicit grouping.

2.1. Participants

Eighty undergraduates (58 female, mean age = 20.7 years, SD = 2.9, $N = 40$ in Experiment 1a, and $N = 40$ in Experiment 1b) from University of British Columbia (UBC) participated for course credit. Participants had normal or corrected-to-normal vision, and provided informed consent. All experiments were approved by UBC Behavioral Research Ethics Board.

2.2. Stimuli

Stimuli consisted of ten colored circles (circle diameter subtended 1.4°). The circles were generated from a pool of ten distinct colors (color name = R/G/B values: red = 255/0/0; green = 0/255/0; blue = 0/0/255; yellow = 255/255/0; magenta = 255/0/255; cyan = 0/255/255; gray = 185/185/185; orange = 255/140/0; brown = 103/29/0; black = 0/0/0). Eight circles were randomly assigned for every participant into four 'color pairs'. The remaining two circles were not paired. The single circles ensured that both even and odd numbers were presented in the experiment. The four pairs were grouped into fixed horizontal, vertical, and diagonal configurations (Fig. 1A).

The number of circles in each array ranged from 10 to 20, creating 11 levels of numerosity. An array with 10 circles contained 4 pairs + 2 singles. An array with 11 circles contained 4 pairs + 3 singles (2 singles + 1 single randomly chosen from the 2). An array with 12 circles contained 4 pairs + 2 pairs randomly chosen from the 4 pairs. An array with 13, 14, or 15 circles contained 4 pairs + 2 pairs chosen from the 4 pairs, and 1, 2, or 3 singles, respectively. For 16–20, all pairs were repeated once. In addition, for 17–20, 1, 2, 3, or 4 singles were presented, respectively. Each array was placed on an invisible 5×5 grid (subtending $10.3° \times 10.3°$), with the constraint that each pair neighbored at least one other pair or one single circle. This ensured that statistical learning could not solely be determined by spatial segmentation cues other than co-occurrence. Each level of numerosity was repeated 40 times, resulting in 440 trials (order randomized for every participant).

2.3. Apparatus

In all experiments, participants seated 50 cm from a computer monitor (refresh rate = 60 Hz). Stimuli were presented using MATLAB (Mathworks) and the Psychophysics Toolbox (http://psychtoolbox.org).

2.4. Procedure

Participants were randomly assigned to one of two conditions: structured or random ($N = 20$ in each). During exposure, participants in both conditions viewed arrays of colored circles and estimated the number of circles in each array. They were told that each array contained 10–20 circles, and entered their estimate by typing one of 11 keys, with each key corresponding to one number ('∼' = 10, '1' = 11, '2' = 12...'9' = 19, '0' = 20). Each array was presented for 500 ms followed by an inter-stimulus interval (ISI) of 500 ms. If the participant responded within the 500 ms presentation time, the next trial appeared after the ISI; otherwise the screen remained blank until response.

In the structured condition, each array contained the pairs and/or single circles. To ensure incidental encoding of regularities, participants were not informed about the pairs. In the random condition, each array was identical to that in the structured condition, except that after the pairs were placed on the grid, their positions were randomly shuffled (Fig. 1A). This eliminated the color pairs, but maintained the spatial layout, the number and the density of the circles.

After completing all estimation trials, participants in the structured condition completed a test phase. In each trial, two sets of circles were presented for 1000 ms, one on the left and one on the right side of the screen. Participants pressed a key to indicate whether the left ('1' key) or right ('0' key) set seemed more familiar. One set was a pair, and the other 'foil' set contained one color from the pair and one color from a different pair. The colors in the foil had never appeared in this spatial configuration. Each pair was tested against two foils: The first foil contained one color from the pair, and the second foil contained its other color. Each pair-foil combination was tested twice, creating 16 trials (order randomized). Because all individual colors were equally frequent during exposure and test, participants could only choose the pair as more familiar if they had learned color co-occurrences. There was no test phase in the random condition since no pairs were presented during exposure.

After test, a debriefing session was conducted, where participants were asked if they noticed any colored circles that appeared with one another. For those who responded yes, we further asked them to specify which colors co-occurred.

2.5. Results and discussion

During test, the pairs were chosen over foils for 50.9% of the time, which was not reliably above chance (50%) [$t(19) = 0.28$, $p = .78$, $d = .06$]. During debriefing, 6 participants reported noticing the pairs, but none correctly reported which two specific colors co-occurred. This suggests that participants had no explicit awareness of the color pairs.

To address how regularities influenced numerosity estimation, we calculated errors by subtracting the objective numerosity from the estimated numerosity. Thus, a negative error means underestimation, a positive error means overestimation, and zero means perfect accuracy. We compared the errors across the 11 numerosity levels between the two conditions (Fig. 1B). A 2 (condition: structured vs. random; between subjects) × 11 (numerosity levels; within subjects) mixed-effects ANOVA revealed a main effect of numerosity levels [$F(10,380) = 199.75$, $p < .001$, $\eta_p^2 = .84$], with greater underestimation as numerosity levels increased. Importantly, there was a main effect of condition [$F(1,38) = 4.87$, $p = .03$, $\eta_p^2 = .11$], with greater underestimation in the structured condition than in the random condition. Moreover, the interaction was reliable [$F(10,380) = 3.83$, $p < .001$, $\eta_p^2 = .09$], with greater underestimation in the structured condition compared to the random condition, at higher levels of numerosity than at lower levels.