Details on stimuli generation for Experiment 1 & 3

Experiment 1

Proximity grouped displays contain six clusters of circles arranged in a 3 by 2 matrix, with 3-5 circles in each cluster. Each cluster was drawn within a rectangle of 2.7° by 3.7° and the average distance between two neighboring cluster was 8.1° horizontally and 10.1° vertically. Corresponding control displays were created by selecting 24 cells without replacement from an 8 by 5 grid (3.4° by 3.2° for each cell in the grid) and placing one dot at a random location within each selected cell. The overall area occupied by the controlled display was the same as the grouped displays. Each circle was 1.0° in diameter.

For the connectedness-grouping and common-region-grouping condition, both the grouped and their control displays were made up of outline circles, again each 1.0° in diameter. Their positions were chosen in the same way as the control displays for proximity grouping. In the connectedness-grouped display, 24 of these circles were connected to form 6 non-overlapping polygons, with 3-5 adjacent circles serving as vertices of each polygon. The clustering of these circles, i.e. which circles should belong to the same polygon, is determined by the method of K-means. In the common-region-grouped display, 24 circles were enclosed by 6 non-overlapping bubbles, with 3-5 circles as internal vertices of each bubble. The clustering of these circles is also determined by the method of K means.

For the similarity-grouping conditions, icon positions for both grouped and control displays were set in the same way as the control displays for proximity grouping. Each display contained six spatially-localized groups of icons: circles (1° in diameter) for color grouping; shapes (1.4° by 1.4°; triangle, clover, oval, square, T-shape, and X-shape) for shape grouping; and arrows (1.3° by 1.7°; up, down, left, right, and the four diagonals between them) for orientation grouping. The set of colors consisted of red (RGB value: 190,0,0), green (RGB value: 49,126,0), blue (RGB value: 0,97,168), orange (RGB value: 165,84, 0), purple (RGB value: 130,0,169), brown (RGB value: 124,111,0), and cobalt (RGB value: 0, 48,145). On grouped displays, neighboring icons were of the same color, or shape, or orientation, creating 6 unique spatially-localized color, shape, or orientation groups with the 3-5 icons forming each group. The clustering of these circles, i.e. which icon should belong to the same similarity group, is determined by the method of K means. Ungrouped control displays contained a homogenous set of objects of a feature value not present in the grouped display.

Experiment 3

In the number estimation task, similarity-grouped and its control displays were generated similarly to Experiment 2. 24 cells were randomly selected from a 7 by 5 grid (3.6° by 3.5° for each cell in the grid) and one icon was placed at a random location within each selected cell. Each similarity group consisted of 3-6 objects and the group assignments are determined by the method of k-means. For the proximity grouped displays, we set the between-group distance to be 1.6 times the within-group distance. This ratio was acquired through a strength matching measurement before number estimation experiment, described in more detail in the following section. To create proximity-grouped displays, we first created six proximity groups with 3-6 objects, the average inter-object distance in these groups were 2.8° horizontally and 2.7° vertically. These groups were then placed in a 3 x 2 grid. The distance between two neighboring groups was calculated by first finding the maximum distance between two neighboring objects within each group along each axis, dmax_X and dmax_Y, then comparing dmax_Xs (/dmax_Ys) of two horizontally (/vertically) neighboring group and multiplied the larger one by 1.6. This number was used to set the horizontal (/vertical) distance between the two closest dots from each group, as illustrated in Figure 1. The control display for proximity-grouped condition consist of dots interspersed within the same area as the proximity-grouped display. Their positions were chosen in the same way as the control displays for proximity grouping in Experiment 1. Overall, all displays occupied the same area of 24.5° by 17.3° center screen.

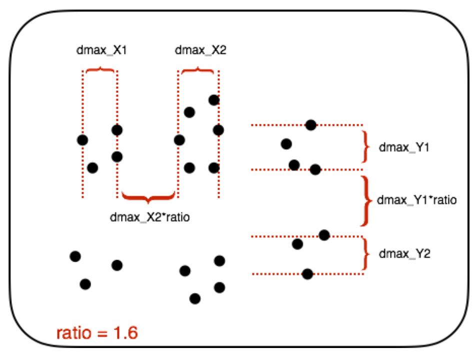

Figure 1. Illustration of the object arrangement on the proximity-grouped display in Experiment 3.

Additional Experiment: Making spatial grouping cues inhibitable

We rely on the fact that spatial groupings cause underestimation of number, but similarity groupings do not, to support the idea that feature-based attention underlies similarity grouping. But it is possible that differences in the selection demands of the number estimation task causes this performance dissociation. The task is, to some degree, inherently spatial, in that number is a property of spatially localized objects. This could increase the importance of spatial properties more broadly for the participant. In contrast, object features (color, shape, etc) are irrelevant to the task, and could be actively inhibited by the participant. One way to test this idea is to provide the observers with a way of inhibiting the spatial grouping cues, using feature selection. To test this possibility, we ran new versions of the common region and connectedness conditions, but made the grouping cues (line) a different color from the objects. If the failure to find underestimation in the spatial grouping conditions was due to failures to inhibit spatial grouping cues, then the addition of this new (inhibitable) feature should reduce the underestimation effect for spatial grouping.

Participants

Eight Northwestern University undergraduates and graduate students participated in this experiment in exchange for $5 or course credit. All participants had normal or corrected-to-normal acuity and normal color vision. The number of participants was specified based on power analysis of Experiment 2: with the effect size of 1.65 regarding to the estimation bias in common-region grouping conditions, 8 participants are needed to detect similar estimation bias in the current experiment with the power of 95%.

Stimuli & Procedure

Experimental stimuli were identical to the common region and connectedness conditions from Experiment 1 except that the connecting bars in the connectedness condition, as well as the broken bars in its control, were colored red, while the circles remained black. Similarly, the enclosing contours in the common region condition were colored red while the circles remained black. The experimental procedure was otherwise identical to Experiment 1.

Results & Discussion

The underestimation effect persisted as strongly as in Experiment 1. Enclosing the circles with red bubbles biased observers to significantly underestimate its quantity (17.4 vs. 23.3 in control, $t(7) = 5.72$, $p=.001$, Cohen's $d = 2.02$, 95% CI = [.76, 3.25]). Connecting circles with red lines also result in similar underestimation (16.4 vs. 23.8 in control, $t(7) = 5.09$, $p=.001$, Cohen's d

=1.80, 95% CI = [.63, 2.93]). Spatial grouping appears strong and automatic, operating independently of the processing of nonspatial features (e.g. color). Of course, the present work cannot rule out the possibility that a properly motivated participant could construct similarity groups in parallel within an enumeration task, and we hope that future work continues to test whether other tasks might reveal this ability.