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Nonlinear dynamics in the perceptual grouping of connected surfaces

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ABSTRACT

Evidence obtained using the dynamic grouping method has shown that the grouping of an object's connected surfaces has properties characteristic of a nonlinear dynamical system. When a surface's luminance changes, one of its boundaries is perceived moving across the surface. The direction of this dynamic grouping (DG) motion indicates which of two flanking surfaces has been grouped with the changing surface. A quantitative measure of overall grouping strength (affinity) for adjacent surfaces is provided by the frequency of DG motion perception in directions promoted by the grouping variables. It was found that: (1) variables affecting surface grouping for three-surface objects evolve over time, settling at stable levels within a single fixation, (2) how often DG motion is perceived when a surface's luminance is perturbed (changed) depends on the pre-perturbation affinity state of the surface grouping, (3) grouping variables promoting the same surface grouping combine cooperatively and nonlinearly (super-additively) in determining the surface grouping's affinity, (4) different DG motion directions during different trials indicate that surface grouping can be bistable, which implies that inhibitory interactions have stabilized one of two alternative surface groupings, and (5) when alternative surface groupings have identical affinity, stochastic fluctuations can break the symmetry and inhibitory interactions can then stabilize one of the surface groupings, providing affinity levels are not too high (which results in bidirectional DG motion). A surface-grouping network is proposed within which boundaries vary in salience. Low salience or suppressed boundaries instantiate surface grouping, and DG motion results from changes in boundary salience.

1. Introduction

Perceptual organization has been an active area of experimental research from the earliest days of Gestalt psychology to the present (for extensive reviews see Wagemans, Elder, et al., 2012, Wagemans, Feldman, et al., 2012). Over this long history, studies of perceptual organization have been concerned almost exclusively with the grouping of spatially separate, disconnected surfaces that are arranged in regular grids (Wertheimer, 1912) or lattices (Kubovy & Wagemans, 1995). Valuable grouping principles have been identified using this method. In one example, a grid is composed of disconnected surfaces that differ in shape (Fig. 1a). How the surfaces are grouped for this stimulus usually is perceptually evident. That is, most if not all observers likely will agree on the grouping in which the surfaces are organized into vertical columns rather than horizontal rows, consistent with of the grouping principle of shape similarity.

Despite its success, there are two reasons why the grid/lattice method cannot be used to study perceptual organization for objects. The first is the obvious fact that objects are composed of connected rather than disconnected surfaces. The second is that in contrast with stimuli like the one in Fig. 1a, the organization of connected surfaces is not necessarily revealed by their perceptual appearance (Fig. 1b and c).

Hock and Nichols (2012) and Hock (2014) have proposed a new, quantitative method for studying the perceptual organization of objects composed of connected surfaces. Their method determines the overall grouping strength, or *affinity*, for pairs of adjacent surfaces by perturbing the luminance of one of the surfaces. The perturbation changes the surface's luminance similarity with its adjacent surfaces, and thereby, its affinity with those surfaces. For example, changing the luminance of the right-hand surface in Fig. 2 induces what Hock and Nichols (2012) call *dynamic grouping* (*DG*) *motion* across the changing surface. It appears as if a moving boundary of the changing surface is "painting" the new (Frame 2) luminance value across the surface. The percept is similar to the line motion illusion (Hikosaka, Miyauchi, & Shimojo, 1993; Hock & Nichols, 2010; von Grünau, Saikali, & Faubert, 1995).

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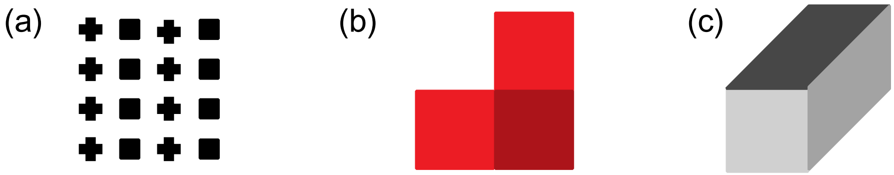

Fig. 1. (a) Example of grids with disconnected surfaces. (b) and (c) Examples of objects with connected surfaces.

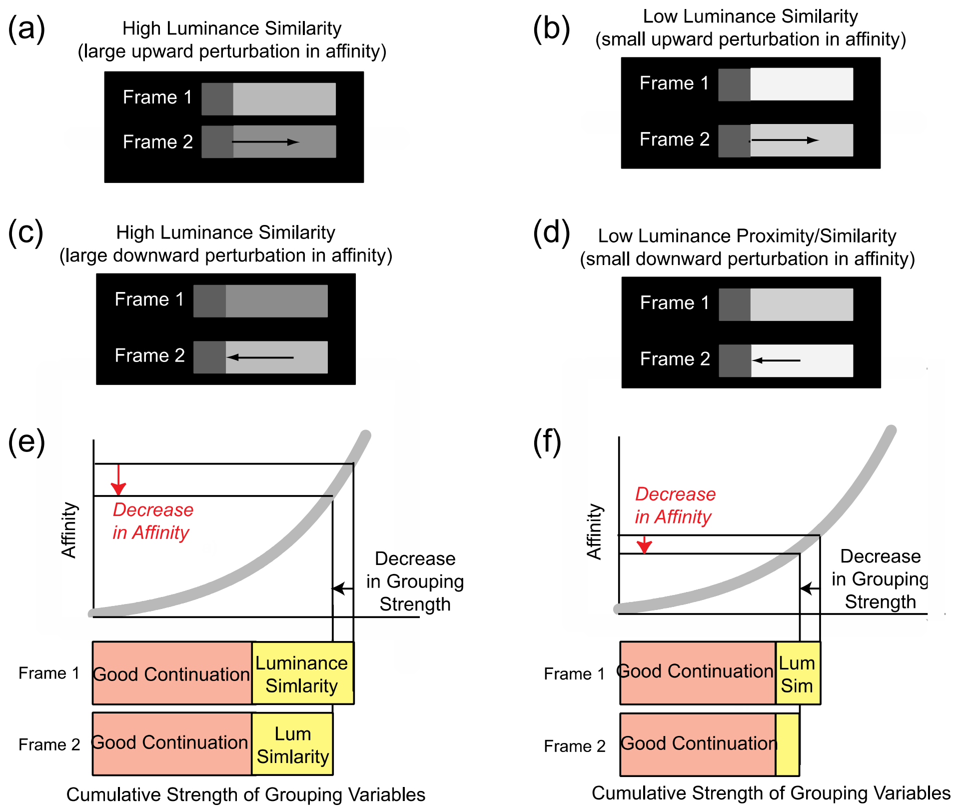

Fig. 2. (a and c) Stimuli for which surface affinity during Frame 1 is promoted by the presence of relatively high luminance similarity. (e) When the luminance similarity is decreased during Frame 2, as in (c), there is a large decrease in the affinity of the two surfaces because the perturbation in luminance similarity occurs where the slope of the function relating accumulated grouping strength to affinity is relatively steep. (b) and (d) Stimuli for which affinity during Frame 1 is weakly promoted by the presence of relatively low luminance similarity. (f) When the luminance similarity is decreased during Frame 2, as in (b and d), there is a small decrease in the affinity of the two surfaces because the same perturbation in luminance similarity occurs where the slope of the function relating accumulated grouping strength to affinity is less steep. The perception of DG motion is more likely when the change in affinity is larger, as in (e). The motion depends on changes at both vertical boundaries of the horizontal bar, beginning near the boundary with the square and ending near the opposite boundary of the horizontal bar when luminance similarity increase, and vice verse when luminance similarity decreases.” Although connectivity (Palmer & Rock, 1994) contributes to surface grouping for all the stimuli tested in this study, it always is matched for the two flanking surfaces. It therefore is omitted from the graphs in this figure and the figures that follow.

DG motion is in characteristic directions for pairs of adjacent surfaces, depending on whether the affinity of the surfaces has been increased or decreased. For the stimuli in Fig. 2a and b, when the luminance of the horizontal bar decreases, its luminance similarity with the darker square increases, and DG motion is perceived across the horizontal bar, away from its vertical boundary with the square, toward the vertical boundary on the other side of the horizontal bar. This direction of the DG motion reflects an increased tendency for the two surfaces to be grouped together to form a larger unit, decreasing the *salience* of the boundary separating them. Conversely, when the luminance of the horizontal bar increases, its luminance similarity with the square decreases (Fig. 2c and d), and DG motion is perceived across the horizontal bar, away from the vertical boundary on the right side of the horizontal bar, toward the vertical boundary separating the two surfaces. This motion direction reflects a decreased tendency for the two surfaces to be grouped together, increasing the salience of the boundary separating them.

1.1. State dependence and super-additivity

As indicated above, the tendency for a pair of adjacent surfaces to be grouped, or unified – their affinity – is inversely related to the salience of the boundary separating the surfaces. Because it phenomenologically entails the motion of the changing surface's boundaries, it is likely that transient changes in boundary salience are responsible for the perception of DG motion, consistent with Lu and Sperling's (1995) salience-based 3rd-order motion system. The relationship between surface grouping and DG motion is elaborated in the theoretical framework presented in Section 9.

The proportion of trials for which DG motion is perceived as a result of perturbing a grouping variable (e.g., luminance similarity)