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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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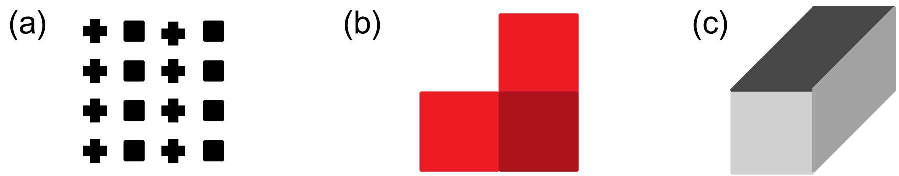

Fig. 1. (a) Example of grids with disconnected surfaces. (b) and (c) Examples of objects with connected surfaces.

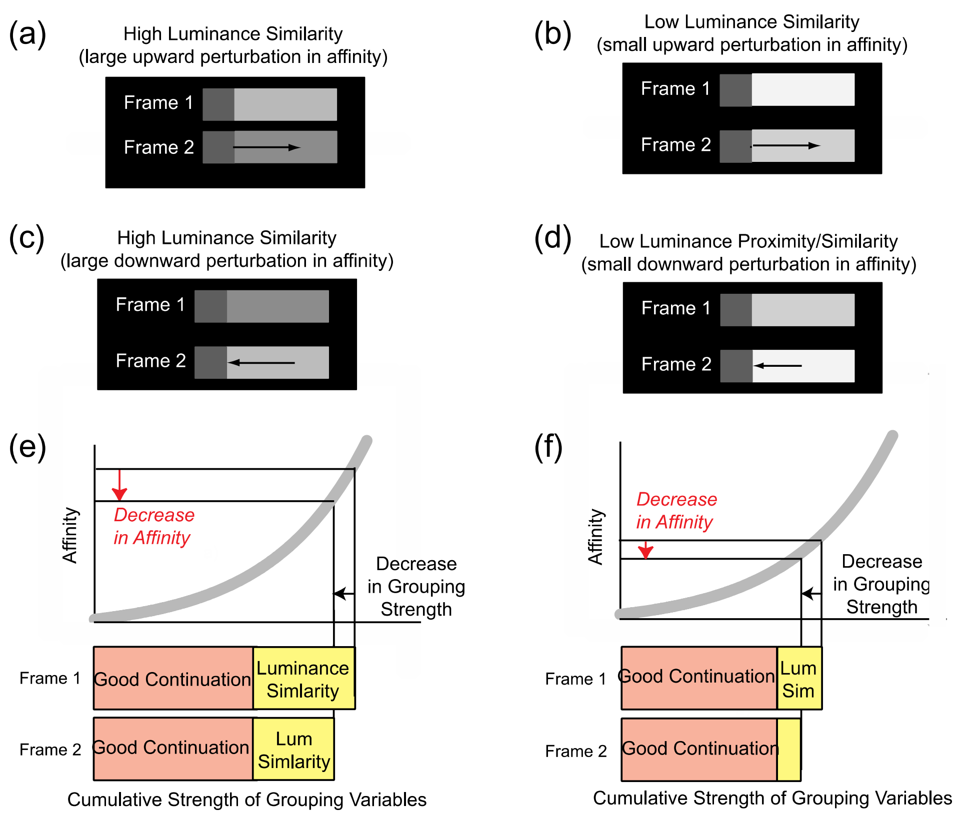

Fig. 2. (a and c) Stimuli for which surface affinity during Frame 1 is promoted by the presence of relatively high luminance similarity. (e) When the luminance similarity is decreased during Frame 2, as in (c), there is a large decrease in the affinity of the two surfaces because the perturbation in 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) provides a quantitative measure of the over-all grouping strength (affinity) of pairs of adjacent surfaces. Hock and Nichols (2012) showed that a luminance perturbation is more likely to produce a change in affinity that is sufficient to induce DG motion when the pre-perturbation luminance of the surfaces is more similar (Fig. 2a and c). This *state dependence* for the stimuli with high and low levels of luminance similarity was accounted for by the accelerating nonlinear functions in Fig. 2e and f, which relate the combined effect of multiple grouping variables to the affinity of a pair of adjacent surfaces. That is, affinity increases at a faster rate than the summed strength of the grouping variables that contribute to the affinity; i.e., their combined effect on affinity is *super-additive*. As a result, greater pre-perturbation affinity for a pair of surfaces "places" their affinity higher on the nonlinear, super-additive function (Fig. 2e) than the surfaces with less pre-perturbation affinity (Fig. 2f). The same perturbation of luminance similarity therefore produces a larger change in affinity when the two surfaces are initially more similar in luminance, increasing the likelihood that DG motion will be perceived.

1.2. The surface correspondence problem

The dynamic grouping method becomes a valuable *diagnostic* tool when it is possible for a surface to be grouped with two or more other surfaces, which creates the *surface correspondence problem* (Hock & Nichols, 2012); i.e., the visual system must determine which surface goes with which, analogous to the motion correspondence problem (Ullman, 1979).

DG motion, which occurs during the second frame of each two-frame trial, results from the perturbation of the surface groupings that were determined during Frame 1. The perceived DG motion is diagnostic with respect to the nature of those surface groupings, but surface grouping and DG motion neither occur at the same time, nor do they involve the same processes. Edge detection at surface boundaries and other spatial mechanisms (e.g., detection of co-linearity) determine the surface grouping structure of a multi-surface object, whereas transient changes in boundary salience caused by the perturbation of the already established grouping structure are responsible for the perception of DG motion.

Hock and Nichols (2012) showed how the visual system resolves the surface correspondence problem with test stimuli derived from one of Tse, Cavanagh, and Nakayama's (1998) examples. Hock and Nichols's (2012) version also was composed of a horizontal bar that was flanked by an adjacent vertical bar on one side and an adjacent square on the other, but with all three surfaces present during both frames of every 2-frame trial (Fig. 3a)[1]. The presence of good continuation (the horizontal boundaries of the square and horizontal bar are co-linear) "places" the pre-perturbation affinity state at a higher level of the super-additive grouping/affinity function for the grouping of the horizontal bar with the square (Fig. 3b) compared to its grouping with the vertical bar (Fig. 3c). On this basis, it is hypothesized that the horizontal bar is grouped with the square more often than it is grouped with the vertical bar when the surface grouping structure of the object is established by the end of the first frame. This was confirmed by the direction of the perceived DG motion when the already established surface grouping was perturbed during Frame 2.

The effect of a perturbation is "as if" only the two surfaces grouped during Frame 1 were present. When that surface grouping is perturbed, DG motion is in the characteristic directions described in Section 1.1; i.e., toward the boundary between the grouped surfaces if their affinity is decreased during Frame 2 and away from the surface boundary if their affinity is increased during Frame 2. The direction of DG motion during Frame 2 therefore depends on the surfaces that had been grouped during Frame 1, and whether the Frame 2 perturbation increased or decreased the affinity of the grouped surfaces. When affinity is decreased, the direction of DG motion effectively "points" at the boundary of the grouped surfaces. If the alternative surface grouping were formed during Frame 1, the DG motion would "point" in the opposite direction because the boundary of the alternative surface grouping is on the opposite side of the central surface.

In the example in Fig. 3, DG motion usually was perceived in directions indicative of the horizontal bar being grouped with the square rather than the vertical bar. That is, motion was perceived across the horizontal bar toward the square when their luminance similarity was decreased (as in Fig. 2c and d), and away from the square when their luminance similarity was increased (as in Figs. 2a, 2b, and 3a). Thus, the surface correspondence problem was resolved most often in favor of the surface grouping with the greater affinity. (Although it is not addressed in this article, the dynamic grouping of unconnected surfaces is possible when they are separated by an occluding surface (Fig. 10 in Hock & Nichols, 2012).

1.3. Surface grouping and unit formation

The likely function of surface grouping for multi-surface objects is to form independent units, or parts, that can be the basis for determining whether the parts belong to the same or different objects, and for recognizing the objects. A simple demonstration of grouped surfaces forming independent units is based on the stimulus in Fig. 3. For this stimulus, the horizontal bar and square are grouped on the basis of their affinity being greater than the affinity of the horizontal and vertical bars. Rightward DG motion predominates when the luminance similarity of the surfaces is increased, even when a small gap is inserted between the horizontal and vertical bars. Thus, the grouped surfaces form an independent unit that is unaffected by whether or not there is a shared boundary with the vertical bar. This indication of unit formation is confirmed by inserting the gap is between the square and the horizontal bar. Leftward DG motion now is perceived across the horizontal bar because it is now is grouped with the adjacent vertical bar. The change in the direction of DG motion occurs because the grouping and unification of the horizontal bar and square is no longer possible.

1.4. Objectives

The overall objective of the research reported in this article is to provide quantitative evidence that the perceptual organization of an object's surfaces and boundaries has properties that are characteristic of a nonlinear dynamical system. The test stimuli were geometric objects composed of three connected surfaces, all of which were visible during both frames of every 2-frame trial. Good continuation and hue similarity were static grouping variables; they remained the same during both frames. Luminance similarity was the dynamic grouping variable. When the luminance of the middle surface was changed during the second frame, its affinity with each adjacent surface was simultaneously perturbed, inducing the perception of DG motion across the changing surface. From the direction and strength of the perceived DG motion, it was determined in Experiment 1 whether the affinity of a surface grouping is cooperatively enhanced (or inversely, the salience of the boundary separating the surfaces is reduced) when multiple grouping variables promote the same surface grouping. Whether the grouping variables combine non-additively, and thus

[1] In Tse, Cavanagh, and Nakayama (1998), the horizontal bar is present only during the second of two frames and the perceived motion is referred to as "transformational apparent motion."

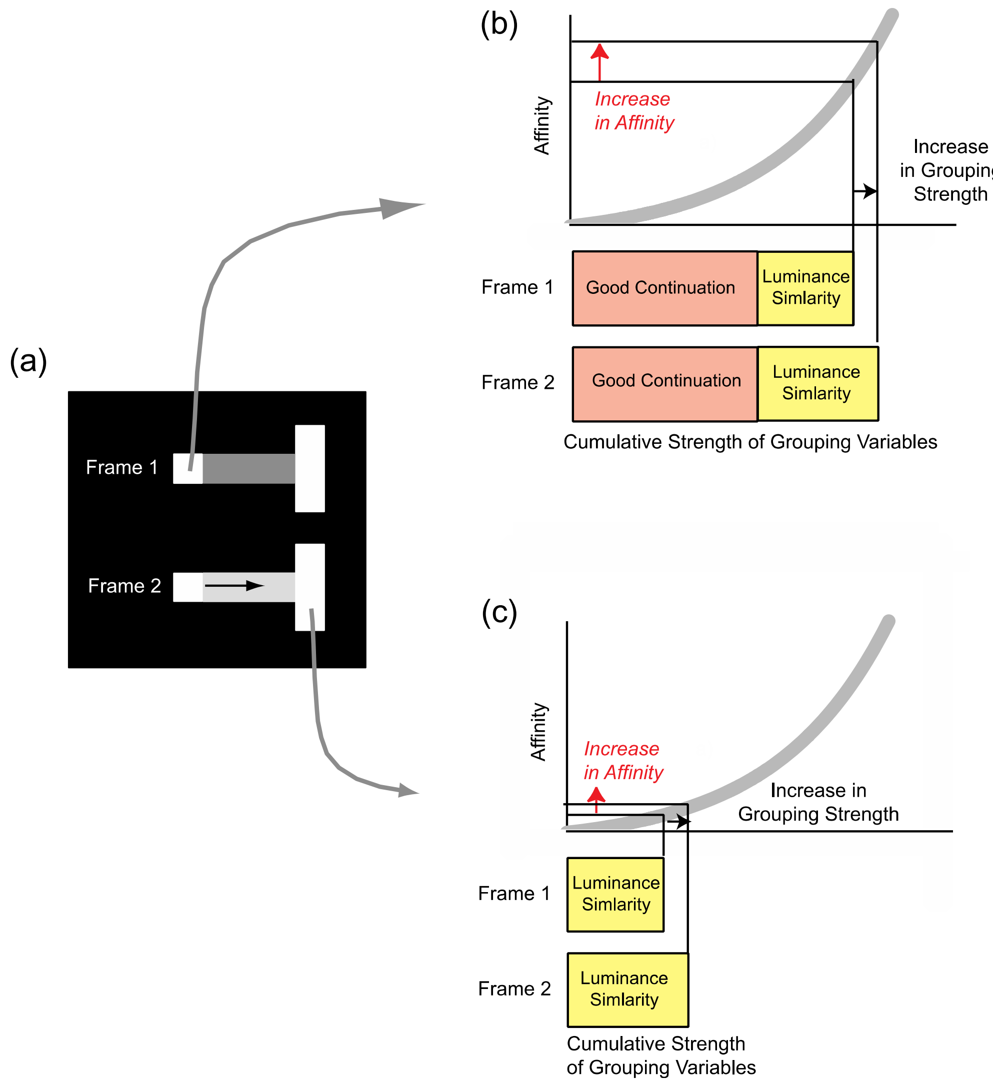

Fig. 3. (a) Stimulus from Hock and Nichols (2012). During Frame 1 the horizontal bar has greater affinity with the square than with the vertical bar because the grouping with the square is promoted by good continuation. When the luminance similarity is increased during Frame 2, there is a greater increase in the affinity of the horizontal bar with the square (b) than with the vertical bar (c) as a result of the perturbation occurring where the slope of the function relating grouping strength to affinity is steeper. This results in the perception of dynamic grouping motion away from the square.

nonlinearly, in determining the affinity relationships among object's surfaces was tested in Experiment 2. The first two experiments therefore tested a feature of surface grouping that is central to the dynamic grouping method. That is, the effects of multiple grouping variables combine super-additively in determining the affinity of two surfaces.

Frame duration was varied in order to determine the approximate time course for the perceptual organization of a multi-surface object to stabilize. This includes parsing the object's surfaces, detecting the surfaces' boundaries, and determining affinity for pairs of the parsed surfaces (or equivalently, the salience of their boundaries), which evolve toward steady-state values. The latter values are called 'attractors' in nonlinear dynamics (Hock & Schöner, 2010). When steady state values are reached, it can be determined whether the same surface grouping is always stabilized, even though another is conceivable (monostability), or whether either surface grouping can occur, though one might occur more often (bistability). The purpose of Experiment 3 was to obtain definitive evidence for bistability, and thus the presence of inhibitory interactions that stabilize one or the other of the alternative surface groupings. In Experiment 4, the grouping variables promoting the alternative surface groupings were exactly matched. It was determined whether the perception of DG motion is affected by the affinity levels of the alternative surface groupings.

2. General method

2.1. Stimuli

The stimuli were two-dimensional geometric objects composed of three connected surfaces. They were presented in the center of a Mitsubishi Diamond Pro 930SB monitor with a refresh rate of 120 Hz. The viewing distance, 30 cm, was maintained with a head restraint. The duration of the first frame of each 2-frame trial was 8.3, 16.7, 25, 33.3, 41.7, 50, 100, or 150 ms. The duration of the second frame was 500 ms.

The middle of the three surfaces composing each stimulus was a red horizontal bar (4.4 × 1.1 deg of visual angle). It was flanked on each side by squares (1.1 × 1.1 deg) and/or vertical bars (1.1 × 3.3 deg) that were either red or blue. The four combinations of shape and color (red square, blue square, red vertical bar, blue vertical bar) were presented equally often on the left or right side of the horizontal bar. The luminance of the red horizontal bar was 12.5 cd/m^2 during the duration-varying first frame. It remained red during the 500-ms second frame, but its luminance was decreased to values between 3.5 and 6.3 cd/m^2, adjusted for each subject in order to avoid floor and ceiling effects in the perception of DG motion.

The luminance values of the blue and red flankers were 12.5 and 15.6 cd/m^2, respectively. The luminance of the red flankers was greater than the luminance of the horizontal red bar (12.5 cd/m^2 during the first frame) in order for those surfaces to be visually distinct. This imbalance in pre-perturbation luminance similarity was small and the same in every condition within each experiment, so it was not a factor in the results.

In Experiments 1–3, different combinations of grouping variables promoted each of the alternative surface groupings. In Experiment 4, the grouping variables were identical for each of the alternative surface groupings.

2.2. Procedure

A small 0.3×0.3 deg red fixation square (luminance = 12.5 cd/m^2) was presented for 1500 ms prior to the start of each trial, but not during the trial. It was located in what would be the center of the horizontal bar when the 3-surface stimulus was presented. Subjects were instructed to maintain their attention at this location throughout the trial. After each 2-frame stimulus presentation they were instructed to press one of two designated keys on the computer keyboard with their left hand in order to indicate whether or not motion was perceived, and then to press one of three designated keys with their right hand in order to indicate whether the motion was leftward, rightward, or in both directions at the same time (i.e., bidirectional).

2.3. Subjects

Five undergraduate students at Florida Atlantic University voluntarily participated in two or more of the first three experiments. Three additional students participated in Experiments 4. All were naïve with respect to the purpose of the experiments.

2.4. Ethics

This work was carried out in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki).

3. Data analysis

Analysis of the results for Experiments 1–3 were based on the proportion of the total number of trials during which unidirectional DG motion was perceived in directions predicted by the pre-perturbation affinities of the alternative surface groupings. If DG motion were perceived in the opposite direction with sufficient frequency, it would indicate that the surface grouping determined by the dynamic grouping method is bistable. If the perceived DG motion were overwhelmingly in one direction, a single, monostable surface grouping would be indicated.

Motion often was not perceived in these experiments, especially for brief first-frame durations. Data analyses could have been based on the proportion of motion-perceived trials in directions predicted by the relative affinities of the alternative surface pairs. However, this would have resulted in the vast over-estimation of the effectiveness of the grouping variables of interest for brief frame durations. For example, if DG motion were perceived during only 8 of the 200 trials with the briefest first-frame duration, and 5 of these motion-perceived trials were in the direction predicted by differences in pre-perturbation affinity, only a few responses would be incorrectly signifying a strong effect of a grouping variable on the affinity of pairs of surfaces. For this reason, proportions were based on the total number of trials (4.0% in this example) instead of the number of motion-perceived trials (67.5% in this example)[2].

4. Experiment 1: cooperativity

In this experiment, good continuation and hue similarity promoted the same surface grouping, either singly (Fig. 4a and b) or together (Fig. 4c). It was anticipated that DG motion would be perceived in the direction determined by the perturbation of the surface grouping promoted by the two grouping variables more often when they were jointly present than when they were singly present. This would indicate that when together, the two grouping variables cooperatively enhanced the affinity of the surface grouping that they jointly promoted.

4.1. Method

Four subjects were tested during four sessions, each composed of 6 blocks of trials: two each for the ‘good continuation alone’, the ‘hue similarity alone’, and the ‘combined good continuation and hue similarity’ conditions (in counterbalanced order). A total of 80 order-randomized trials per block was determined by the orthogonal combination of 2 flanker positions (each flanker was on the left and right sides of the horizontal bar), 8 durations for the first frame of each trial, and 5 repetitions. The second-frame luminance for the horizontal bar was 6.3 cd/m^2 for three subjects and 4.3 cd/m^2 for one subject.

4.2. Results

Presented in Fig. 4d are the mean proportions of trials for which unidirectional DG motion was perceived toward the blue square in the ‘good continuation alone’ condition, and toward the red vertical bar in the ‘hue similarity alone’ and the ‘combined good continuation and hue similarity’ conditions (solid lines). These DG motion directions were predicted by the perturbation of the surface groupings promoted by each grouping variable and their combination. Steady-state levels were approached for first-frame durations of approximately 100–150 ms. This showed that it was possible to parse the stimulus’ surfaces, determine their boundaries, and establish pre-perturbation affinity relationships within a single fixation.

Included in Fig. 4d are the mean proportions of trials for which DG motion was perceived in directions opposite to the directions indicative of the surface grouping promoted by hue similarity and good continuation (broken lines). Bistability was indicated for the ‘hue similarity alone’ condition; DG motion was perceived more frequently in the direction predicted by the perturbation of the surface grouping promoted by hue similarity, but it also was perceived in the opposite direction (the trials for which motion was not perceived are not included in the graph). The bistability indicated that either of the alternative surface groupings, when simultaneously perturbed, could be the basis for the perception of DG motion. In contrast, monostability was indicated for good continuation; i.e., DG motion almost always was perceived in the

[2] With the exception of Experiment 4, bidirectional motion was perceived very infrequently. The exception was one subject in Experiment 2, whose data were excluded.

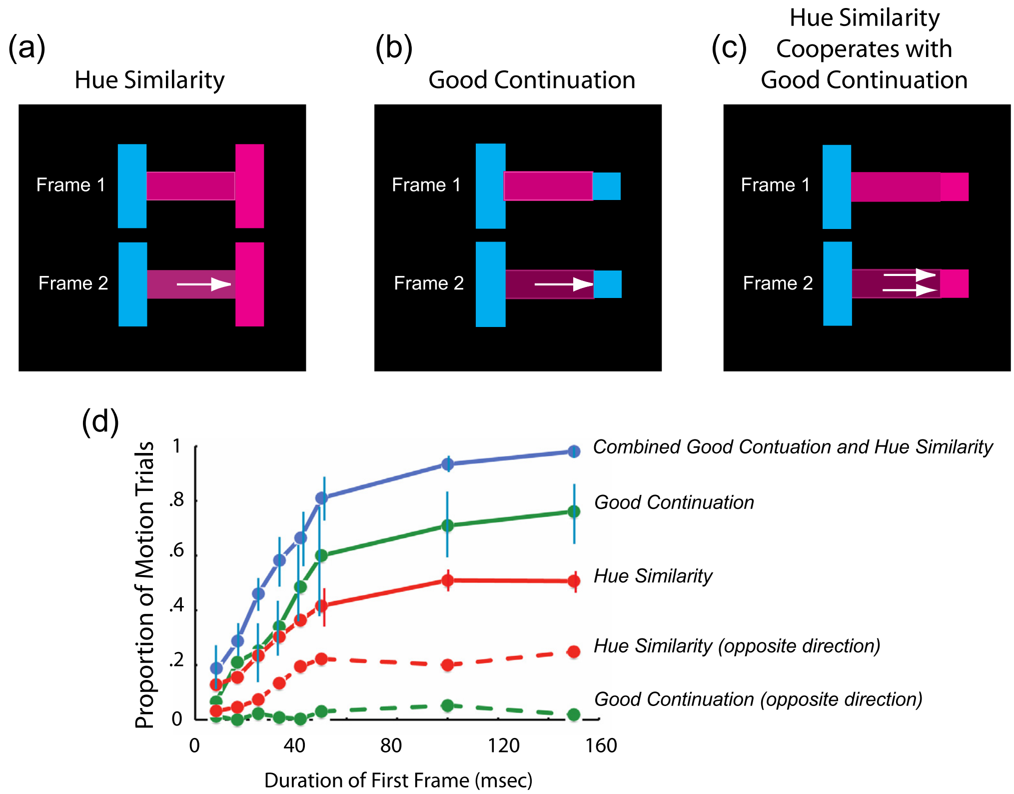

Fig. 4. Experiment 1: (a–c) Stimuli (d) Results. The solid lines indicate the proportion of trials during which dynamic grouping (DG) motion was perceived in directions determined by the perturbation of the surface grouping that is promoted by the grouping variables. The broken lines indicate the proportion of trials in which DG motion was perceived in the opposite direction. There were very few reports of 'opposite direction' motion in the 'Combined' condition; they are not included in the graph. Also not included are the proportions of trials for which motion was not perceived (see Section 3) and the infrequent trials for which perceived motion was bidirectional. Plus and minus one standard error bars are presented where they would be visible, providing they are larger than the markers that indicate each mean value.

direction determined by the perturbation of the surface grouping promoted by good continuation. The monostability indicates that if there were motion-inducing shifts in attention (Cavanagh, 1992), they were unlikely to have significantly influenced the results. Otherwise, motion would have been perceived in the opposite direction for many more of the trials in the 'good continuation alone' condition, which would have undone the observed monostability.

To test for cooperativity, the proportion of trials for which DG motion was perceived for the 'combined good continuation and hue similarity' condition was compared to the proportion perceived in the 'good continuation alone' condition (there was more DG motion for the latter than for the 'hue similarity alone' condition). The difference across the eight first-frame durations was statistically significant, $F(1,3) = 14.16$, $p < .05$, indicating that the promotion of the same surface grouping by two grouping variables cooperatively enhanced the affinity of the surface grouping (compared with a single grouping variable). The difference was less than standard errors of measurement for the brief first-frame durations (some error bars are omitted because of crowding). The effect of cooperativity emerged most clearly for the longest first-frame durations, when the perceptual organization of the three-surface object stabilized. (The effect of luminance similarity on surface grouping is not discussed here because luminance similarity was the same in all the conditions within each of the first three experiments, so their outcomes were not affected. The effect of luminance similarity on the perception of DG motion – in the absence of good continuation and hue similarity – is tested in Experiment 4; Section 7.)

5. Experiment 2: nonlinear summation

If the function relating grouping strength to affinity were nonlinear, it would imply that the combined effect of two or more grouping variables is non-additive in determining how pairs of surfaces are grouped together. Evidence for nonlinear summation was expected on the basis of the preceding experiment and Hock and Nichols' (2012) account of their results with a super-additive function relating the combined effects of cooperating grouping variables to the affinity of pairs of adjacent surfaces (see Figs. 2 and 3 in Sections 1.1 and 1.2).

Nonlinearity was tested in this experiment by having good continuation symmetrically promote the grouping of the horizontal bar with each of its two flanking surfaces. In this way, the presence of good continuation provided a pedestal for hue similarity, whose effect on surface grouping was asymmetrical. That is, hue similarity promoted the grouping of the horizontal bar with only one of its flanking surfaces. If the combined effects of the grouping variables on affinity were additive (i.e., if they combined linearly), the alternative surface pairings that were symmetrically promoted by good continuation would be balanced, so changes in affinity when the alternative surface groupings were perturbed would be unaffected by the presence of good continuation (Fig. 5a); DG motion therefore would be perceived equally often in the direction determined by hue similarity, with and without the good continuation pedestal. If, however, the combined effects of the grouping variables on affinity were non-additive (i.e., if they combined nonlinearly), the presence of good continuation would provide a pedestal for hue similarity such that their combined effects on affinity would

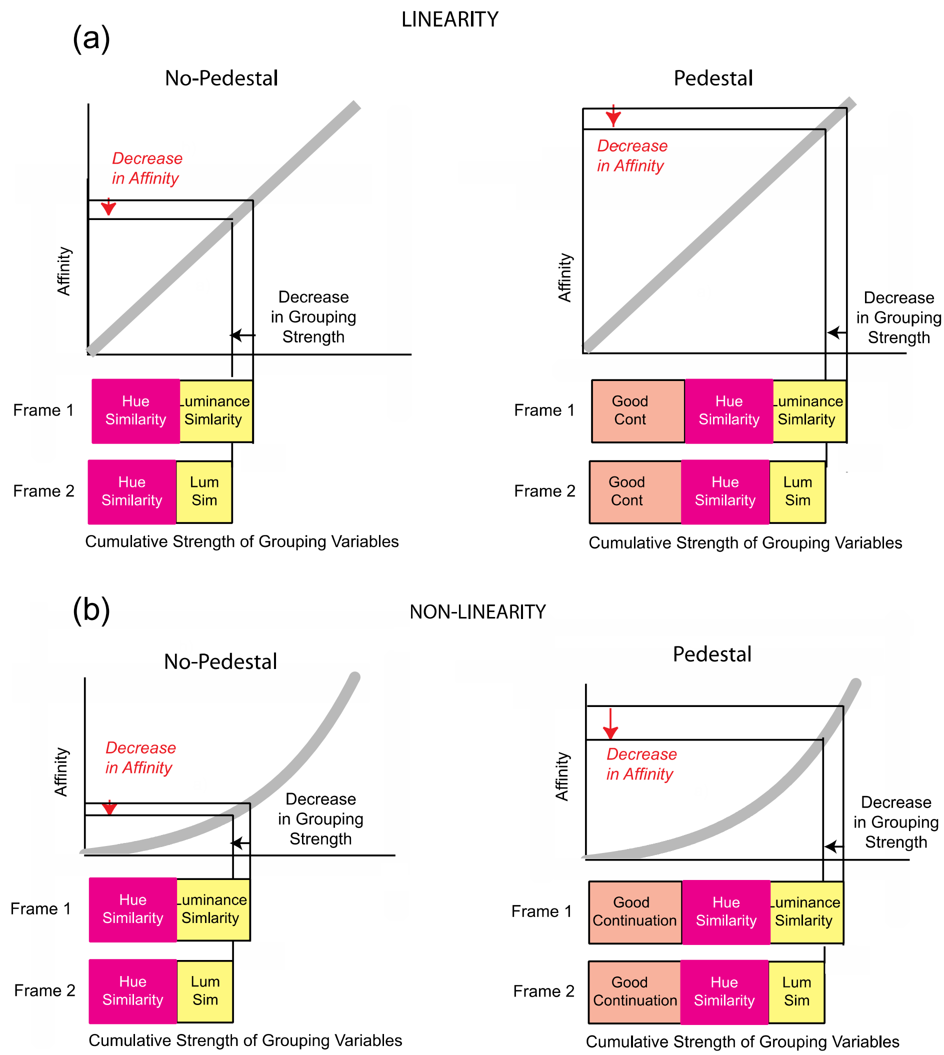

Fig. 5. Alternative outcomes for Experiment 2. (a) For a linear, additive relationship between accumulated grouping strength and affinity, the same luminance perturbation produces the same change in affinity in the No-Pedestal and Pedestal conditions, and therefore, the same perception of dynamic grouping motion. (b) With a nonlinear, super-additive relationship between accumulated grouping strength and affinity, the same luminance perturbation produces a larger change in affinity in the Pedestal than the No-Pedestal condition, and therefore, more frequent perception of dynamic grouping motion in the Pedestal condition.

exceed the sum of their individual effects (assuming the nonlinearity is super-additive, as in Fig. 5b). DG motion then would be perceived in the direction determined by the surface grouping promoted by hue similarity more often with than without the presence of the good continuation pedestal.

5.1. Method

Stimuli with and without the good continuation pedestal are illustrated in Fig. 6a and b. Four subjects were each tested during four sessions, each of which was composed of four blocks of trials: two each with and without the good continuation pedestal (in counterbalanced order). As in Experiment 1, there were 80 order-randomized trials per block. The first-frame luminance of the horizontal bar was 12.5 cd/m^2. Its luminance during the second frame was 3.5 cd/m^2 for three subjects and 4.2 cd/m^2 for one subject.

5.2. Results

Indicated by solid lines in Fig. 6c are the mean proportions of trials for which unidirectional DG motion perception was toward the red square when the good continuation pedestal was present, and toward the red vertical bar when good continuation was not present. These are the directions indicative of surface grouping promoted by hue similarity (and good continuation when it was present). As in Experiment 1, the proportion of trials during which DG motion was perceived in this direction increased with increases in first-frame duration, then flattened for first-frame durations of 100 and 150 ms.

In the condition without the good continuation pedestal, DG motion was perceived more often in the direction determined by the perturbation of the surface grouping promoted by hue similarity, but it also was perceived in the opposite direction (as was the case for hue similarity in Experiment 1). In contrast to this evidence for bistability, monostability was indicated when good continuation was present (also as in Experiment 1).

Across the eight first-frame durations, unidirectional DG motion was perceived in the direction expected from the perturbation of the surface grouping promoted by hue similarity significantly more often when the good continuation pedestal was present, $F(1,3) = 65.28$, $p = .004$. The pedestal effect was clearly present when the perception of DG motion for the grouping variables reached steady-state (attractor) levels.

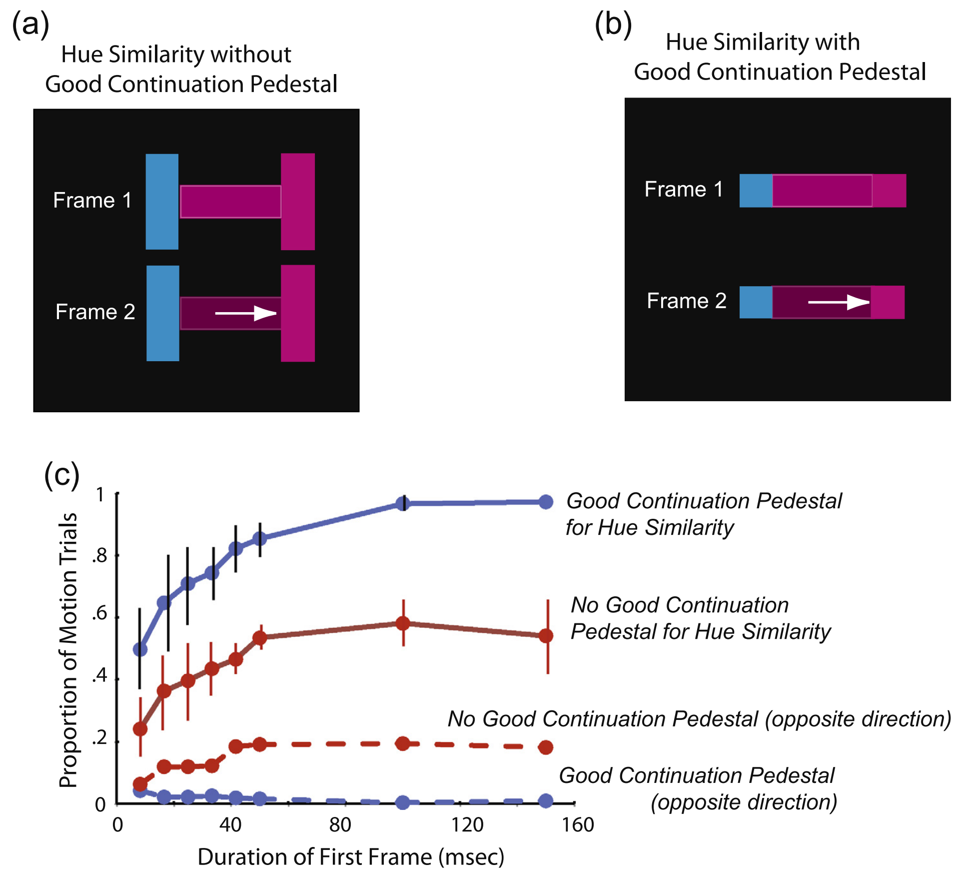

Fig. 6. Experiment 2: (a and b) Stimuli. (c) Results. The solid lines indicate the proportion of trials during which dynamic grouping motion was perceived in directions determined by the perturbation of the surface grouping that was promoted by hue similarity, with and without the good continuation pedestal. The broken lines indicate the proportion of trials for which motion was perceived in the opposite direction. Not included are the proportions of trials for which motion was not perceived (see Section 3) and the infrequent trials for which perceived motion was bidirectional. Plus and minus one standard error bars are presented when they are larger than the markers.

The results indicated, therefore, that the effects of good continuation and hue similarity combined non-additively (nonlinearly). As illustrated in Fig. 5b, the pedestal effect in this experiment can be accounted for by the super-additive nonlinearity proposed by Hock and Nichols (2012). That is, the effect of the good continuation pedestal was to "place" the effect of hue similarity at a higher level with respect to the function relating combined grouping strength to pre-perturbation affinity. As a result, the same luminance perturbation produced a greater change in affinity, and thereby, stronger DG motion in the direction determined by the perturbation of the surface grouping with the greater pre-perturbation affinity.

6. Experiment 3: inhibitory competition

In the preceding experiments, DG motion was frequently perceived in the direction promoted by hue similarity (when good continuation was not a factor), it also was perceived in the opposite direction, but for only 20% or less of the trials. Although these results were consistent with bistable surface grouping, it was possible that the infrequent perception of DG motion in the opposite direction was due to experimental artifacts. That is, some subjects may not have consistently attended to the fixation dot; e.g., fixating closer to the vertical bar might increase the likelihood of DG motion toward that surface. Directional biases were another possibility. Some subjects might have been biased to perceive motion in one direction at the expense of the opposite direction, irrespective of the DG motion direction predicted from the perturbation of the surface groupings.

The purpose of this experiment was to create a more definitive bistability in which opposite DG motion directions, induced by the simultaneous perturbation of the alternative surface groupings, were similar in frequency. This was accomplished by having hue similarity promote the grouping of the horizontal bar with one flanking surface, and good continuation promote the grouping of the horizontal bar with the other flanking surface (Fig. 7a). Four subjects were tested with 8 blocks of 80 order-randomized trials, determined as in the preceding experiments.

6.1. Results

As in the preceding experiments, the perception of unidirectional DG motion increased with increases in first-frame duration, and flattened for first-frame durations of 100 and 150 ms (Fig. 7b). Once these steady-state values were reached, the proportion of trials for which unidirectional DG motion was perceived in the direction determined by the perturbation of the surface grouping promoted by hue similarity was similar to the proportion in the direction determined by the perturbation of the surface grouping promoted by good continuation. This evidence for bistability implies the presence of inhibitory interactions that stabilize one or the other of the alternative surface groupings.

7. Experiment 4: breaking symmetrical affinity

In the preceding experiments, the alternative surface groupings were each promoted by different combinations of grouping variables. The surface correspondence problem usually was resolved

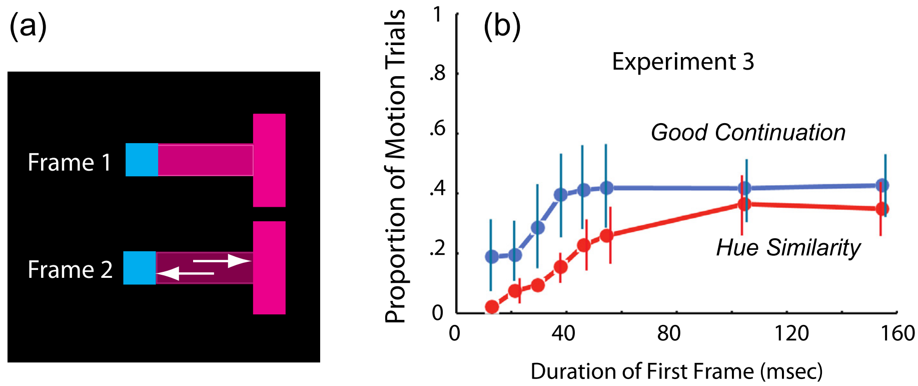

Fig. 7. Experiment 3 (a) Stimulus. (b) Results. The proportion of trials during which dynamic grouping motion was perceived in directions determined by the perturbation of the surface grouping that was promoted by hue similarity, and by the perturbation of the competing surface grouping that was promoted by good continuation. Not included are the proportions of trials for which motion was not perceived (see Section 3) and the infrequent trials for which perceived motion was bidirectional. Plus and minus one standard error bars are presented where they would be visible, and are larger than the markers indicating mean values.

on this basis. That is, one or the other of the alternative surface groupings was stabilized and unidirectional DG motion was perceived in directions consistent with the perturbation (during Frame 2), of the surface grouping that was stabilized during Frame 1. The purpose of this experiment was to determine whether the inhibitory interactions that are necessary for the stabilization of one of the alternative surface groupings also would be effective when the alternative surface groupings were equally promoted by the same grouping variables. Affinity levels were varied by varying the number of cooperating grouping variables, and thus, the affinity level for each of the alternative surface groupings. As illustrated in Fig. 8, there either were three grouping variables (good continuation, hue similarity, and luminance similarity), two grouping variables (hue similarity and luminance similarity or good continuation and luminance similarity), or one grouping variable (luminance similarity) that contributed equally to the affinity of the alternative surface groupings.

It was anticipated that this symmetry would be broken by stochastic fluctuations, and as in the preceding experiments, unidirectional DG motion would be perceived in either direction. It also was anticipated that the perception of unidirectional DG motion would depend on the number of cooperating grouping variables contributing to the symmetrical affinity of the alternative surface groupings.

7.1. Method

Unlike the preceding experiments, the duration of the first frame of each 2-frame trial always was 1000 ms. The duration of the second frame remained at 500 ms. The horizontal bar always was red. Its luminance was 12.7 cd/m^2 during the first frame and 3.2 cd/m^2 during the second frame. The luminance of the flanking surfaces was 13.9 cd/m^2, regardless of their shape or hue. A white fixation dot was present prior to and during the first frame (luminance = 62.3 cd/m^2). Each of the four stimulus conditions, which are illustrated in Fig. 8a–d, was tested in blocks of 80 order-randomized trials (4 stimuli, each repeated 20 times). Keyboard responses were as in the preceding experiments.

7.2. Results

The mean results for three, two and one grouping variable are presented in Fig. 8e. The data are averaged for the two directions of unidirectional DG motion that were reported (left and right), and for the two conditions in which there was good continuation but not hue similarity, and vice versa.

It can be seen that unidirectional DG motion was perceived (and the surface correspondence problem resolved), but mostly when the affinities of the alternative surface groupings were determined by one or two grouping variables. The symmetry breaking that resulted in the perception of unidirectional DG motion was indicative of stochastic fluctuations in affinity, plus inhibitory interactions that stabilized the surface grouping that was advantaged by the stochastic fluctuations. Preliminary testing suggested that the stochastic fluctuations also could produce spontaneous changes in the direction of DG motion, potential evidence for spontaneous switches in surface grouping.

The surface correspondence problem was not resolved when three grouping variables determined the affinity of the alternative surface groupings. Instead, the perception of bidirectional DG motion predominated. Nor was it always resolved when one grouping variable determined the affinity of the alternative surface groupings; motion often was not perceived.

These results and those obtained in the preceding experiments, indicated that the surface-grouping network, which will be described in Section 9, has four stable surface-grouping states for the three-surface stimuli studied in this article, each with a corresponding DG motion pattern obtained when these stable states are perturbed (de-stabilized) by the perturbation of luminance similarity: (1) two of the three surfaces are grouped; unidirectional DG motion is perceived in one direction, (2) a different two out of the three surfaces are grouped; unidirectional DG motion is perceived in the opposite direction, (3) all three surfaces are grouped; bidirectional DG motion is perceived (simultaneous motions in opposite directions), and (4) no surface grouping; no perception of DG motion in either direction.

8. General discussion

In Experiments 1–3, the alternative surface groupings were asymmetrical. That is, they were distinguishable by virtue of being promoted by different combinations of grouping variables. The experiments determined the proportion of trials for which the perception of DG motion was in directions consistent with the grouping of adjacent surfaces on the basis of good continuation and/or hue similarity (luminance similarity promoted both surface groupings). A perturbation that simultaneously decreased the luminance similarity of the horizontal bar with both of its flanking surfaces resulted in the perception of DG motion across the horizontal bar, usually toward the flanking surface with which it had the greater pre-perturbation affinity.

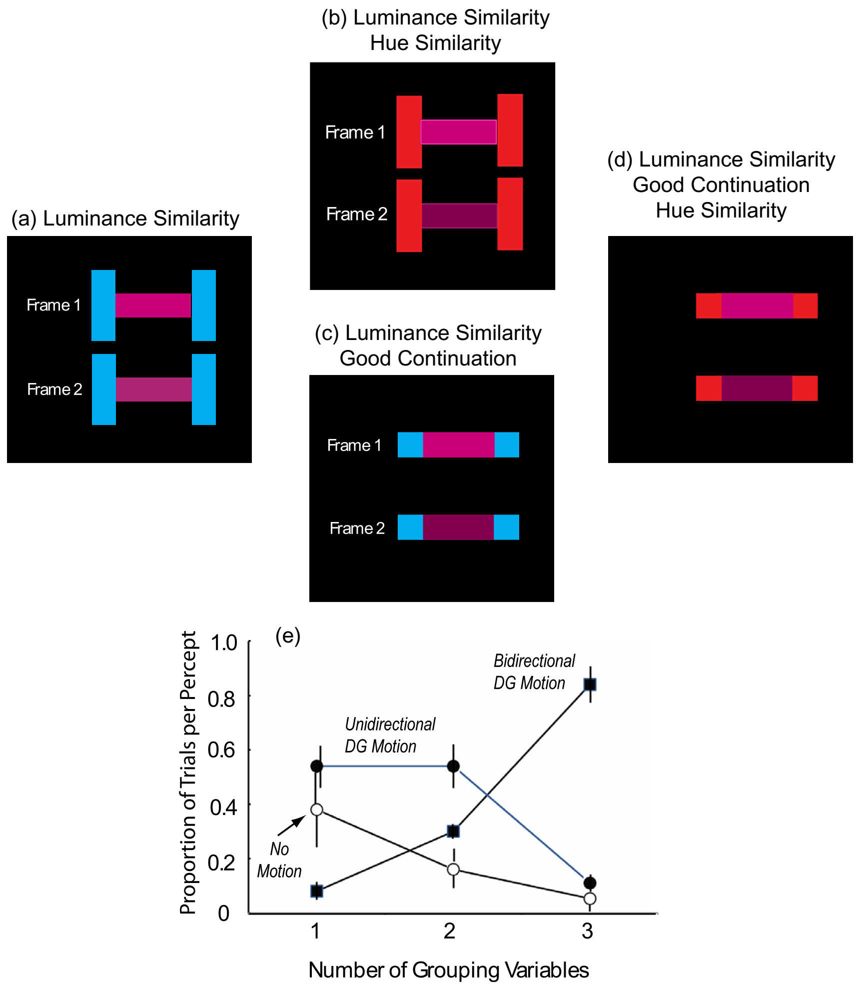

Fig. 8. Experiment 4: (a–d) Stimuli vary with respect to the number of grouping variables contributing symmetrically to the grouping of the central surface with its flanking surfaces. (e) Results. As a function of the number of symmetrical grouping variables, the proportion of trials during which dynamic grouping (DG) motion was unidirectional or bidirectional, and the proportion of trials for which motion was not perceived. Plus and minus one standard error bars are presented, providing they are larger than the markers indicating mean values.

In each of these experiments, the effectiveness of these grouping variables (and their combination) increased with increases in the duration of the first frame of each 2-frame trial. This effect 'flattened' for Frame 1 durations of 100 and 150 ms. However, unpublished experiments have suggested that a range of 100 to 200 ms would provide a better estimate of the time required for the stabilization of the grouping variables determining the perceptual organization of the three-surface object. Although imprecise, this estimate indicates that stabilization can be done within a single fixation.

8.1. Stable states for symmetrical and asymmetrical surface groupings

The alternative surface groupings were symmetrical in Experiment 4. That is, the same grouping variables promoted both of the possible surface groupings.

The perception of bidirectional DG motion for high affinity levels, and the lack of DG motion for low affinity levels, provided evidence that stable states could be formed in which all three surfaces are grouped into the same unit, or none of the surfaces are grouped into the same unit. The perception of unidirectional DG motion provided evidence that two more stable states could be formed in which pairs of surfaces are grouped into the same unit. However, it was not possible to determine whether the grouping of pairs of adjacent surfaces were monostable or bistable. This was because the same grouping variables promoted both of the alternative surface groupings, which made them indistinguishable. The determination of monostability and bistability was possible only when the alternative surface groupings were asymmetrical, as in Experiments 1–3.

8.1.1. Monostability

It was observed in Experiments 1 and 2 that the surface groupings promoted by good continuation were monostable; i.e., the direction of DG motion always was consistent with the horizontal bar being grouped with a flanking square whose horizontal boundaries were aligned with those of the horizontal bar. The effectiveness of good continuation shows that in addition to attributes of the surfaces (e.g., hue, luminance), affinity is affected by grouping variables that involve spatial relationships determined by the boundaries of surfaces. The observation of monostability was important because it showed that it is possible even for relatively impoverished three-surface stimuli, and that motion-inducing shifts in attention (Cavanagh, 1992) minimally affected the perception of unidirectional DG motion. If attention shifts had influenced the perceived motion direction for a significant number of trials, their effect would have been independent of the random left/right locations of the two flankers. This would have resulted in the frequent perception of motion in the direction opposite to that observed experimentally, which would have eliminated the monostability.

8.1.2. Bistability

Bistable surface grouping was indicated when the DG motion perceived across the horizontal bar sometimes was in the direction determined by the perturbation of a surface grouping that was promoted by one combination of grouping variables, and sometimes was in the direction determined by the perturbation of the alternative surface grouping that was promoted by a different combination of grouping variables. As indicated in the introduction to Experiment 3 (Section 6), the evidence for bistability was marginal in Experiments 1 and 2. Stronger evidence was obtained in Experiment 3. In this experiment, good continuation promoted a surface grouping whose perturbation resulted in the perception of DG motion in one direction, and at the same time hue similarity promoted an alternative surface grouping whose perturbation resulted in the perception of DG motion in the opposite direction. Both motion directions occurred with similar frequency during different trials, providing definitive evidence for bistability, and thereby, the presence of inhibitory interactions that stabilized one or the other of the alternative surface groupings.

8.2. Dynamic characteristics of surface grouping

The results of Experiments 1 and 2 provided confirming evidence that the combined effect of cooperating grouping variables on the affinity of a pair of surfaces is super-additive. It was found in Experiment 1 that the joint promotion of the same surface grouping by two grouping variables cooperatively enhanced the affinity of the surface grouping, and the pedestal effect in Experiment 2 showed that the cooperating grouping variables combined non-additively, and thus nonlinearly, in enhancing the affinity of the surface grouping. Overall, the four experiments reported in this article indicated that the perceptual organization of the three-surface objects in this study had characteristic features of a nonlinear dynamical system:

(1) The variables determining the perceptual organization of an object's surfaces evolve over time, eventually settling at steady-state levels (i.e., near 'attractors').
(2) Alternative surface groupings can be either monostable or bistable when they are promoted by different combinations of grouping variables.
(3) Bistable surface grouping is indicated when the simultaneous perturbation of alternative surface groupings creates DG motion perception in different directions during different trials. It is indicative of inhibitory interactions that determine which of the surface groupings will be stabilized.
(4) The perception of DG motion is state dependent; changes in the affinity of a pair of surfaces depend on their current affinity state. The greater the pre-perturbation affinity state of a pair of surfaces, the greater the effect of a change in affinity that is produced by a perturbation, and therefore, the greater the likelihood that DG motion would be perceived.
(5) The combination of grouping variables that jointly promote the same surface grouping is cooperative and nonlinear (i.e., super-additive).
(6) Stochastic fluctuations can break the symmetry of alternative surface groupings that are promoted by the same grouping variables, and potentially can produce spontaneous switching between the surface groupings.
(7) Symmetrical affinity levels can be too high for inhibitory interactions to stabilize either of the two alternative surface groupings, or too low for the occurrence of any surface grouping.

9. Theoretical framework for a surface-grouping network

A surface-grouping network is proposed in which different states of the network correspond to different possible surface groupings, including the absence of surface grouping. The network focuses on the boundaries separating the surfaces of multi-surface objects because of the phenomenology of DG motion perception. That is, when DG motion is perceived, it is the boundaries of the changing surface that appear to be moving, "painting" the Frame 2 luminance value across the surface.

9.1. The boundary representation

The first level of the proposed surface-grouping network is similar to Grossberg and Mingolla's (1985a, 1985b) 'boundary contour system', for which boundaries are derived from the edges of an object (the luminance polarity of edge detectors is ignored), but also can be either illusory contours or hidden boundaries, as in amodal completion. Among other perceptual phenomena, Grossberg and Mingolla (1985a, 1985b) applied their theory to the grouping of disconnected surfaces. The proposed surface-grouping network differs in that its aim is to account for the grouping of the *connected surfaces* composing multi-surface objects. At this level, the primary conceptual departure from Grossberg and Mingolla (1985a, 1985b) is that the boundaries separating an object's surfaces, including boundaries between the object and its background, can vary in salience, as determined by the affinity of the surfaces they separate.

Depicted in Figs. 9a and 10a is a stimulus from Experiment 3 for which the directions of DG motion provided evidence that surface grouping was bistable. That is, during different trials perturbations of luminance similarity resulted in approximately equal (and opposite) DG motion perception for the surface grouping promoted by good continuation and the alternative surface grouping promoted by hue similarity. Detected edge information feeds forward to the Boundary representation, and detected surface attributes feed forward to the Filling-In level. The boundaries of an object can be represented as a pattern of salience-determined neural activation along the paths of the boundaries, forming an activation pattern that is spatially isomorphic with the object (Figs. 9b and 10b). The greater the salience of a boundary, the greater the activation of its neural representation, which depends on the inverse of the stimulus variables that combine to determine the affinity of the surfaces that the boundary separates. Greater luminance and hue similarity at the boundary between two adjacent surfaces would contribute to greater affinity of the surfaces, so the neural representation of the boundary between the two surfaces would be relatively low in salience/activation. This would be the case when the input to the Boundary representation comes from edge detectors that respond weakly to low levels of luminance and/or hue contrast (e.g., Johnson, Hawken, & Shapley, 2008).

9.1.1. Spatial mechanisms

The effects of edge detector input on the salience of an object's boundaries are modulated by spatial mechanisms involving the boundaries of the object. The presence of good continuation is established by mechanisms for detecting the alignment of boundaries, and mechanisms for detecting small gaps between parallel boundaries are necessary in order to establish the connectedness of surfaces (Palmer & Rock, 1994). Gap detection is necessary

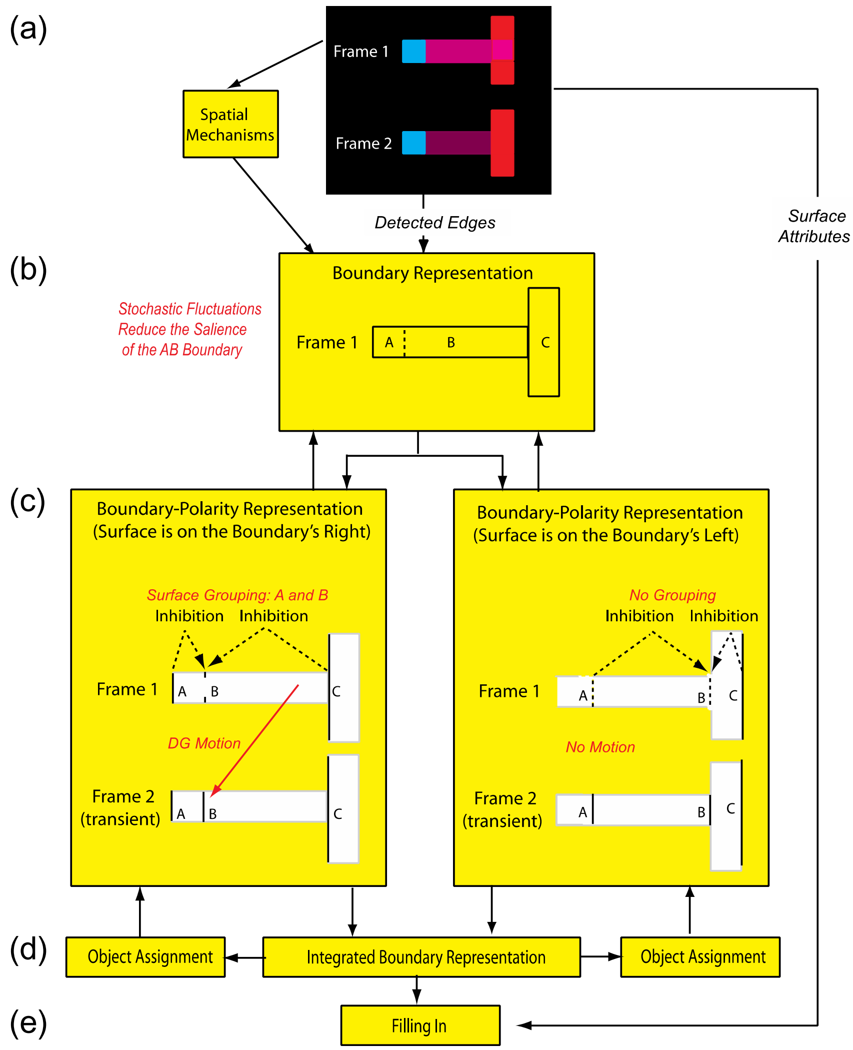

Fig. 9. Theoretical surface-grouping network. (a) Bistable stimulus from Experiment 3. (b) Boundary representation for Frame 1 of 2-frame trial. Stochastic fluctuations result in lower salience for the AB boundary (broken vertical line) than for the BC boundary (solid vertical line). (c) Boundary-Polarity representations separately for vertical boundaries with surfaces to either right or left. Because of their distance dependence, inhibitory interactions have their greatest effect at the location of the central boundary, stabilizing feed-forward determined low-salience boundaries at those locations, and along with recurrent feedback to the Boundary Representation, suppress the AB boundary (as indicated by the tick marks at the top and bottom of the boundary). This instantiates the grouping of surfaces A and B. The perturbation at the start of Frame 2 increases the salience of the AB and BC boundaries in both polarity representations (solid vertical lines), producing a leftward shift in the centroid of the salience values for the vertical boundaries within the right boundary representation, consistent with the perception of leftward dynamic grouping (DG) motion. (d) The Integrated Boundary-representation is the basis for determining whether grouped and ungrouped surfaces are assigned to the same or different objects. (e) Surface attributes "fill in" the Integrated Boundary representation to determine the perceptual appearance of the object, and the experience of a moving boundary "painting" the frame 2 luminance across the horizontal bar.

because edge detectors will respond to the contrast between two surfaces even when a small gap disrupts their connectedness. The activation of a gap detector could suppress inappropriate evidence that separated surfaces are connected, eliminating the possibility that the surfaces would be grouped.

9.1.2. Salience and stochastic fluctuations

Shallow, low-salience boundaries are obtained for surface groupings promoted by multiple grouping variables. This is enhanced by the super-additive effects of the grouping variables on affinity (confirmed by the results of Experiments 1 and 2), and as indicated many times, boundary salience is the inverse of affinity. The grouping of surfaces A and B is initiated by the presence of a low-salience boundary between them (Fig. 9). Similarly, the grouping of surfaces B and C is initiated by the presence of a low-salience boundary between those surfaces (Fig. 10).

Because the results indicated that the alternative surface groupings in Experiment 3 occur with approximately equal frequency (as indicated by the approximately equal frequency of DG motion in opposite directions), obtaining both outcomes of the network depends on their differentiation by stochastic fluctuations, whose presence was indicated by "symmetry-breaking" in Experiment 4 (Section 7). The stochastic fluctuations could result in lower salience for the AB boundary for some trials (illustrated by the vertical broken line in Fig. 9b), and lower salience for the BC boundary for other trials (illustrated by the broken vertical line in Fig. 10b). It will be shown that the stabilization of one or the other of the alternative surface groupings is determined by the location of the lower-salience boundary.

9.2. The Boundary-Polarity representation

Every boundary has a surface on one of its sides and another surface on its other side. On this basis, dual Boundary-Polarity representations are established, one composed of all the vertical boundaries with surfaces on their right, and the other composed

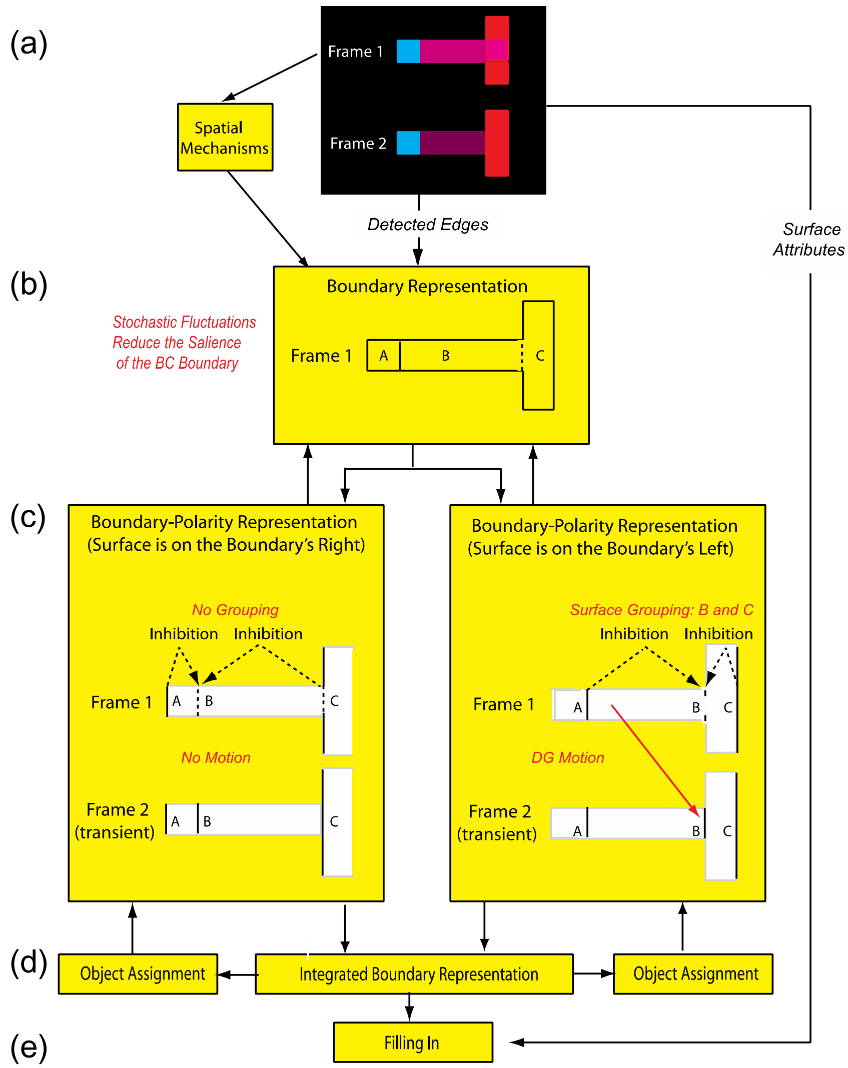

Fig. 10. The same surface-grouping network as in Fig. 9. Also as in Fig. 9, surface grouping is bistable for this stimulus from Experiment 3. In contrast with Fig. 9, stochastic fluctuations result in lower salience for the BC boundary (broken vertical line) than the AB boundary (solid vertical line). Within the Boundary-Polarity representations, inhibitory interactions stabilize the low level of feed-forward determined salience, and along with recurrent feedback to the Boundary representations, suppress the BC boundary (indicated by tick marks at the top and bottom of the boundary). This instantiates the grouping of surfaces B and C. The perturbation at the start of Frame 2 increase the salience of the AB and BC boundaries in both polarity representations (solid vertical lines), producing a rightward shift in the centroid of the salience values for the vertical boundaries within the left Boundary-Polarity representation, consistent with in perception if rightward dynamic grouping (DG) motion.

of all the vertical boundaries with surfaces on their left. For both polarity representations, the sides of boundaries that are the background of the object or parts of another object are excluded. Also excluded are the horizontal boundaries, which are not relevant for the current stimuli.[3] This dual-polarity representation is necessary in order to account for the perception of bidirectional DG motion, and the grouping of all three surfaces into the same unit.

9.3. The stabilization of surface groupings

The surface groupings that constitute two of the four states of the surface-grouping network (corresponding to the alternative surface groupings) are stabilized by recurrent inhibitory interactions and by feed-forward/feedback cycles that increase the difference in salience/activation between the boundary separating one surface grouping and the boundary separating the alternative surface grouping. Increasing the salience/activation difference decreases the susceptibility of the stabilized surface grouping to *de-stabilizing stochastic fluctuations* that would cause the boundary of the alternative grouping to become lower in salience, resulting in a spontaneous switch to the alternative surface grouping (Hock & Schöner, 2010).

9.3.1. Inhibitory interactions

Stabilization due to inhibitory interaction results from the distance-dependence of the inhibitory interactions among all the boundaries within the right-polarity and separately, within the left-polarity representations. The effect of distance dependence is that the combined inhibition from all the vertical boundaries (with the same polarity) is greatest for the central boundaries of the polarity representations. The stabilization of a surface grouping requires feed-forward determined low-salience boundaries to be located where the combined effects of inhibition provide their greatest effect in further reducing the salience of boundaries that already are low in salience. This occurs at the AB boundary,

[3] The surface polarity of a boundary can be thought of as a continuous function. For example, a vertical boundary with a surface on its right is a 90 deg rotation away from a horizontal boundary with a surface above it, and a 180 deg rotation away from a vertical boundary with a surface on its left.

stabilizing the grouping of surfaces A and B (Fig. 9c), *or* at the BC boundary, stabilizing the grouping of surfaces B and C (Fig. 10c). The suppression of one of the inner boundaries does not occur at the BC boundary in Fig. 9b or the AB boundary in Fig. 10b, so the AB and BC surface groupings do are not formed at the same time.

9.3.2. Feedback

In addition to recurrent inhibitory interactions, a surface grouping is stabilized by feedback to the Boundary level from the Boundary-Polarity level of the network. Differences in salience at the Boundary level are initially determined by the stimulus, and in the current case, by stochastic fluctuations. Inhibitory interactions at the Boundary-Polarity level reduce and perhaps suppress the salience/activation of boundaries with low, feed-forward determined salience. Feedback to the Boundary level decreases salience at that level, which in turn feeds forward to the Boundary-Polarity level. Recurrent feedback/feed-forward cycles further stabilize a surface grouping and suppress the salience/activation of the boundary that separates the surfaces.

9.3.3. Boundary suppression and surface grouping

In the current theoretical framework, boundary suppression at the Boundary-Polarity level is a necessary condition for surface grouping. It directly instantiates the joining of two surfaces into one.

9.4. Dynamic grouping (DG) motion

The perturbation of luminance similarity during the second frame of each 2-frame trial increases the salience of both the AB and BC boundaries in the Boundary and Boundary-Polarity representations, temporarily de-stabilizing the previously established surface grouping.[4] Each of the resulting DG motions are determined by salience/activation transients occurring at *both* boundaries of the surface whose luminance is changed during the second frame of each 2-frame trial. The effect of the perturbation is for leftward DG motion to be perceived during Frame 2 if surfaces A and B were grouped during Frame 1 (Fig. 9c), or for rightward DG motion to be perceived during Frame 2 if surfaces B and C were grouped during Frame 1 (Fig. 10c). Possible mechanisms for the perception of these DG motions are described below. But regardless of the particular mechanism, the change in salience due to the perturbation of luminance similarity is much greater for what would have been the low salience (suppressed) boundary during Frame 1 than what would have been the higher salience boundary during Frame 1. This is because changes in affinity/salience are greater for surface groupings that are higher in affinity (due to the super-additive effects of grouping variables on affinity; Sections 1.1 and 1.2). For this reason, the end-points of the motion vectors in Figs. 9c and 10c are at the boundary that had been low in salience (or suppressed) during Frame 1.

9.4.1. Salience energy motion

One possible basis for the perception of DG motion, which is depicted in Figs. 9c and 10c, is for the perturbation to shift the centroid of the vertical boundaries' salience values to the left for the right-polarity representation in Fig. 9c, or to the right for the left-polarity representation in Fig. 10c. (There is no shift for the left-polarity representation in Fig. 9c or the right-polarity representation in Fig. 10c.) Perceived DG motion could then be attributed to the detection of "salience energy" (Lu & Sperling's 3rd-order motion; 1995, 2001), analogous to the detection of luminance-determined motion energy (Adelson & Bergen, 1985).

[4] It remains to be determined whether the de-stabilizing perturbation results in a quantitative change in the affinity of the surface grouping that had been stabilized during Frame 1, or whether it results in a switch to the alternative surface grouping.

9.4.2. Counterchange motion

Another possible basis for the perception of DG motion follows from the inhibitory interactions between the vertical boundaries within the Boundary-Polarity representations. The large increase in salience for what had been the low salience (suppressed) boundary during Frame 1 (e.g., the AB boundary in the right-polarity representation) could sufficiently inhibit what was the higher-salience boundary during Frame 1 (e.g., the BC boundary in the right-polarity representation) to create a net decrease in its salience/activation. This decrease, coupled with the oppositely signed increase in salience/activation for what had been the lower salience boundary during Frame 1, would result in the perception of counterchange-specified motion. The motion would begin at the boundary that decreases in salience/activation and end at the boundary that increases in salience/activation (Hock, Gilroy, & Harnett, 2002; Hock, Schöner & Gilroy, 2009).

9.4.3. No motion

DG motion is not signaled by the left-polarity representation when motion is signaled for the right-polarity representation (Fig. 9c), or by the right-polarity representation when motion is signaled for the left-polarity representation (Fig. 10c). This is the case because the vertical boundary receiving the greatest distance-dependent inhibition is *not* the vertical boundary with the lowest feed-forward salience. As a result, increases in salience are similar for both boundaries of the surface whose luminance is perturbed. Consequently, there is little or no shift in the centroid of the vertical boundaries' salience values (so there is no salience energy), and changes in salience are not oppositely signed (so there is no counterchange). Thus, unidirectional DG motion is signaled by the surface-grouping network. (Bidirectional DG motion is possible when the grouping variables are identical for the alternative grouping variables; Section 9.5.)

9.5. Symmetrical surface groupings

The results of Experiment 4 indicated that when the affinity levels of the alternative surface groupings are equal and not too high, the surface-grouping network settles most often into one of the two states illustrated in Figs. 9 and 10. For this to occur, symmetry must be broken by stochastic fluctuations, and inhibitory interactions and recurrent feedback must stabilize the surface grouping that benefits from the stochastic fluctuations (by having lower salience for the boundary separating the surfaces). The perturbation of luminance similarity for this surface grouping results in the perception of *unidirectional* DG motion in either direction.

When the symmetrical affinity levels of the surface boundaries are increased, as for the stimulus from Experiment 4 (Figs. 8d and 11a), stimulus-determined salience is very low at the locations of both the AB and BC boundaries (the broken vertical lines in Fig. 11b). As a result, the grouping of surfaces A and B is stabilized for the representation in which the boundaries have surfaces on their right, and the grouping of surfaces B and C is stabilized for the representation in which the boundaries have surfaces on their left (Fig. 11c). The effect of the perturbation is to shift the overall salience to the left for the grouping of surfaces A and B (resulting in the perception of leftward DG motion), *and* to the right for the grouping of surfaces B and C (resulting in the perception of rightward DG motion). As indicated previously, the simultaneous leftward and rightward DG motion occurs in the network because of the dual Boundary-Polarity representation. The motions are combined in the Integrated Boundary representation to indicate that bidirectional DG motion is perceived (Fig. 11d).

When symmetrical affinity levels are too low (Fig. 8a in Experiment 4), the boundaries separating the surfaces are too high in salience/activation to be suppressed by Inhibitory interactions and

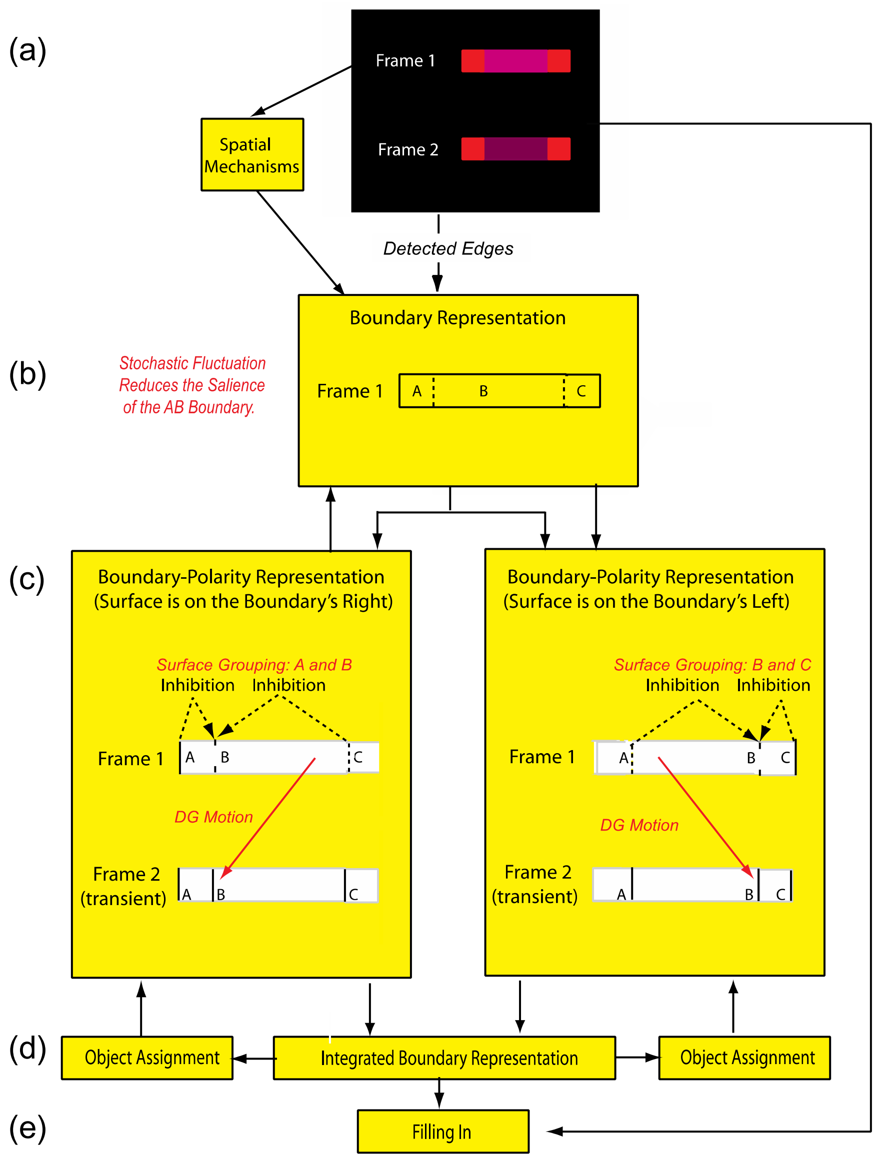

Fig. 11. The same surface-grouping network as in Figs. 9 and 10, but with a stimulus from Experiment 4 for which boundaries AB and BC are both very low in salience (as indicated the broken vertical lines). Inhibitory interactions within each Boundary-Polarity representation stabilize the low levels of feed-forward salience for both boundaries, and along with recurrent feedback to the Boundary representation, suppress them (as indicated by the tick marks at the top and bottom of the boundaries). The Integrated Boundary representation instantiates the grouping of all three surfaces in the same unit (both inner boundaries are suppressed). The perturbation at the start of Frame 2 increases the salience of the AB and BC boundaries in both Boundary-Polarity representation (Solid vertical lines), Producing a leftward shift in the centroid of the salience values for the vertical boundaries within the right-Polarity representation, consistent with the perception of leftward DG motion. There also is a rightward shift in the centroid of the salience values for the left-polarity representation, consistent with the perception of the rightward DG motion. The perception of bidirectional DG motion results from the integration of the right- and left-polarity boundary representations in the Integrated Boundary representation.

recurrent feedback, so no surface groupings are stabilized (even though the first-frame duration was more than long enough for the object's perceptual organization to be completed). Nor is DG motion perceived. Transient changes in salience due to the perturbation of luminance similarity during Frame 2 are small because the low pre-perturbation affinity "places" these potential surface groupings at values for which the super-additive function relating cumulative grouping strength to affinity is relatively flat. As a result, motion-inducing changes in affinity (or boundary salience) are too small to result in the perception of DG motion.

9.6. Integration: object assignment and motion

As indicated in Section 1.3, the likely function of surface grouping for multi-surface objects is to form independent units, or parts. This requires integrating the stabilized surface-grouping structure for each Boundary-Polarity representation. The integration forms parts that are composed of one, two, or three surfaces. It then can be determined whether the parts of a stimulus belong to the same or to different objects. Feedback to the Boundary-Polarity representation prevents the grouping of adjacent surfaces that belong to different objects. This arises most often when one object partially occludes an object that is presumably behind it (as in amodal completion).

The possibility of assigning the parts of a stimulus to different objects cannot arise when all three surfaces are grouped into a single unit, but It can arise for the other three states of the surface-grouping network; i.e., when there are three independent parts and no surface grouping, when the central surface is grouped with one of its flanking surfaces, and when the central surface is grouped with the other flanking surface.

A further effect of integrating the boundary representations with different polarities is to integrate the DG motions determined within each polarity representation, as for the perception of bidirectional DG motion. The integration of motion directions also is indicated for the DG motion that can be perceived for the stimulus illustrated in Fig. 1b. Preliminary testing indicates that when the luminance of the lower right square is decreased, either leftward or upward DG motion can be perceived across the lower-right square. In addition, however, diagonally upward DG motion, the vector sum of the leftward and upward DG motions, can be perceived. This mix of motion directions is analogous to the motion perceived for overlapping sine gratings that drift in different directions. Motion can be perceived in the directions determined by the movement of individual gratings, but the two gratings also can be integrated to form a plaid pattern moving in an intermediate direction (Adelson & Movshon, 1982).

9.7. Filling-in

Consistent with Grossberg and Mingolla (1985a), Grossberg and Mingolla (1985b), it is proposed that the final level in the surface-grouping network entails a process that "fills in" the Integrated Boundary representation with the attributes of each surface. In contrast with Grossberg and Mingolla (1985a), Grossberg and Mingolla (1985b), "filling in" for the surface-grouping network is likely to be affected by the presence of shallow or suppressed boundaries for surface groupings that are high in affinity (low in salience). It is possible, therefore, that there will be mixing of surface attributes between grouped surfaces, at least near the boundary that separates them. This possibility follows from Hsieh and Tse (2006, 2009) evidence for feature mixing across surfaces, which occurs in their experiments when the boundary separating the surfaces perceptually fades out (i.e., disappears). The effects of attribute mixing across grouped surfaces are likely to be subtle, so evidence supporting this conjecture may be elusive.

9.8. The effect of brief exposures

It was estimated in Section 8 that 100 to 200 ms would provide sufficient time for the variables determining the perceptual organization of the three-surface objects in this study to settle at steady-state levels (i.e., near attractors). These first-frame durations are long enough for recurrent feedback and inhibitory interaction to influence perceptual processing (Dehaene, Sergent, & Changeuxt, 2003; Fahrenfort, Scholte, & Lamme, 2008). For the current stimuli, they are long enough to stabilize the grouping of two or more surfaces into the same unit by increasing the difference in salience/activation between low and high salience boundaries. Briefer frame durations would limit the effectiveness of recurrence, so surface grouping would become more reliant on smaller, feed-forward determined differences in salience. This is consistent with the effects of brief first-frame durations in Experiments 1–3. Additionally, brief frame durations would be expected to increase the likelihood of spontaneous changes between alternative surface groupings (see Section 9.9), and in addition, to increase the likelihood of errors in the assignment of surfaces to the same or different objects (for multi-object stimuli).

9.9. Spontaneous switching

The experiments reported in this article have provided evidence for the dynamical basis of surface grouping for the connected surfaces of multi-surface objects. Future research will include experiments addressing some of the signature features of a dynamical system, including the presence of spontaneous switches in surface grouping and hysteresis. In these experiments, decreases and increases in luminance similarity will alternate for the bistable stimulus in Experiment 3 (Fig. 7a), resulting in alternating leftward and rightward DG motion that reflects the grouping of the central surface with one of its flankers. If the left/right alternation of motion direction were spontaneously interrupted, so DG motion is perceived in the same direction during two consecutive frames, it would indicate that there has been a spontaneous switch to the grouping of the central surface with its other flanker.

10. Conclusion

Although the proposed surface-grouping network depends mainly on the boundaries of an object's surfaces, when an object is experienced, its boundaries and surfaces are perceived together (the Filled In representation). It is then possible to sense the relative affinity of pairs of surfaces and to visualize how they could be grouped. Given correct instructions, it might be found that the affinities of alternative surface groupings are correlated with the likelihood of observers visualizing one surface grouping versus another. When the grouping is monostable, it is conceivable that there can be the same degree of observer consensus regarding how the connected surfaces are grouped as there is for grids composed of disconnected surfaces (e.g., Fig. 1a). Consensus notwithstanding, the grouping of disconnected surfaces for stimuli like the one in Fig. 1a seems to have the "advantage" of being perceptually evident. Perhaps that degree of perceptual confidence can be achieved for connected surfaces if the number of cooperating grouping variables for a monostable surface grouping were sufficiently increased. If so, there would be nothing in principle to distinguish the perceptual experience of surface grouping for connected and disconnected surfaces.

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