

# Local versus global perception of ambiguous motion displays

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Four pairs of spots rotating around their common centers, each pair a “doublet”, were arranged in a square formation. The doublets initially appear to rotate “locally”, but then coalesce into two large squares that slide over each other along circular paths (“global” motion). This perceptual transition from local to global motion occurred within and across a series of repeat trials (Experiment 1). Doublet members set close or far apart promoted local or global motion respectively. Increasing the number of spots within a group from two to three or four made the motion look more local. Spots of the same luminance polarity against a gray background tended to move together (Experiment 2); and when replaced by short black lines of different orientations, lines of the same orientation tended to move together, favoring rigid rather than shearing motions (Experiment 3). The perceived trajectories of spots tended to follow static circles or dynamic contours painted on the screen (Experiment 4). These findings suggest the visual system parsimoniously attempts to group the maximum number of moving spots into the minimum number of groups.

**Keywords:** motion-2D, shape and contour, perceptual organization

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## Introduction

A cheetah in a bare cage at the zoo stands out like a spotted fur coat, but in its natural habitat of shrubs and tall grasses its spots provide camouflage. While motion can break this camouflage, from the prey’s point of view the cheetah may still be partially concealed by the undergrowth, and appear as disconnected groups of ambiguously moving spots. In order to perceive the cheetah, the prey must overcome these potential ambiguities and perceive a unified moving entity. Here, we examine some factors that influence the perceptual grouping of moving spots into local or global motion.

Visual ambiguities in perceiving form are well known and tend to exhibit both static and dynamic characteristics. For instance, the Necker cube (Figure 1a) is a static figure that appears to flip back and forth spontaneously in depth, without any change in the physical stimulus. Navon (1977, 1983) found that a large global figure (the letter ‘N’) will generally be identified before the local elements from which it is constructed (the letters ‘S’). This demonstration, shown in Figure 1b, suggests “the forest is seen before the trees”. The global percept occurs initially, and then the large ‘N’ and small ‘S’ characters tend to alternate in salience over time due to an emerging perceptual ambiguity. Since our percepts change even though these static displays do not, Necker cubes and

Navon letters reveal the brain’s computations occurring in real time. While global structures initially tend to be perceived with these static objects, little is known about how perceptual grouping is applied to objects that move globally.

Despite the many possible ways in which moving visual features can be grouped together, we are skilled at linking seemingly ambiguous moving spots together into meaningful structures. For example, when viewing the biological motion of a point-light walker (Johansson, 1973) we reliably perceive a walking human figure. As in the Dry Bones song (Ezekiel 37 1–14), we see the wrist-light [is] connected to the elbow-light [which is] connected to the shoulder-light. The wrist-light never appears to be connected to the hip- or knee-light. The visual system rapidly connects the dots to reveal the point-light walker almost immediately (Johansson, 1973). We can even distinguish the sex, weight and mood of a walker simply from the way the lights move in concert (Troje, 2002). Therefore, percepts of global motion appear to arise from an extensive, high-level analysis of visual motion.

High-level cognitive processes have been implicated in motion transparency perceived from distributed patterns of local motion (e.g., McOwan & Johnston, 1996; Qian, Andersen, & Adelson, 1994). Multiple scene elements can move at the same juxtaposition in the visual field, so there is potential for the motion occurring in one part of the display to be attributed to multiple causes at any one time.

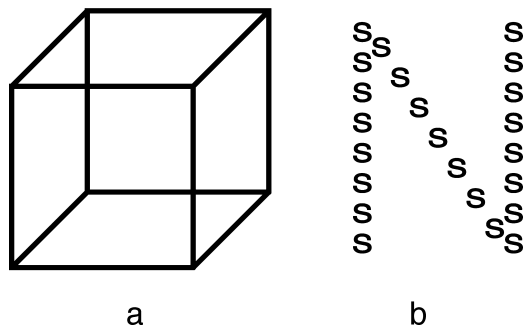
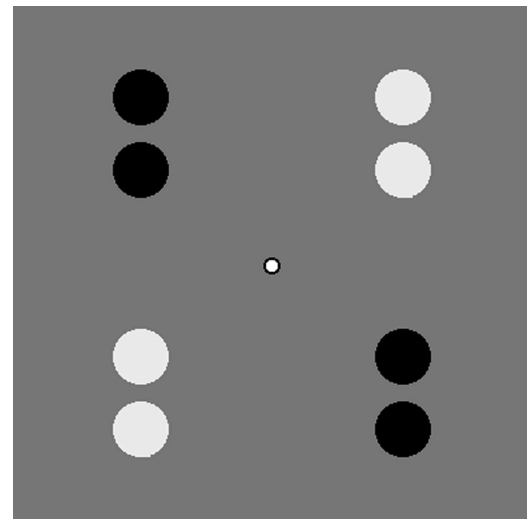


Figure 1. a: A Necker cube flips back and forth perceptually even though it remains static on the page. b: Navon's global letter 'N' is seen before the small 'S' characters from which it is constructed.

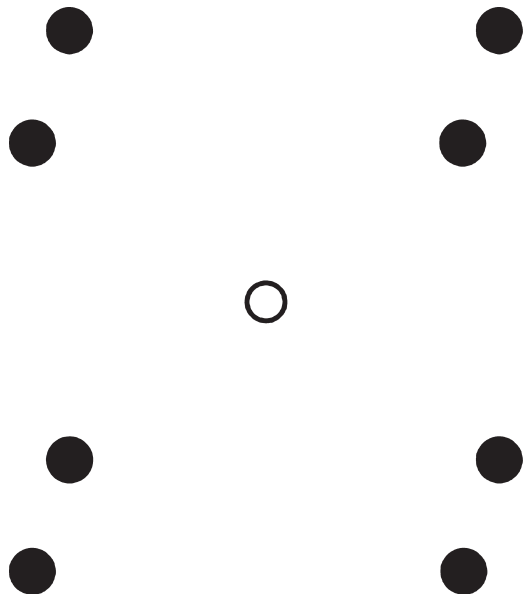
It has been shown that several factors can influence the perception of motion transparency, including distal scene information, luminance, and contrast modulation (e.g., Braddick et al., 1980; Ma-Wyatt, Clifford, & Wenderoth, 2005; McDermott & Adelson, 2004; McDermott, Weiss, & Adelson, 2001; McOwan & Johnston, 1996). McOwan and Johnston (1996) found that the transparent motion of surfaces could be perceived from local 2D arrays of rotating features that were defined by either luminance or local contrast modulation alone. It is possible that common grouping processes underlie the appearance of both static global figures and motion transparency. If so, then the perception of local versus global motion may depend on similar constraints (see also Ramachandran & Anstis, 1985, 1986), which we examine below. These constraints include the time course of learning and



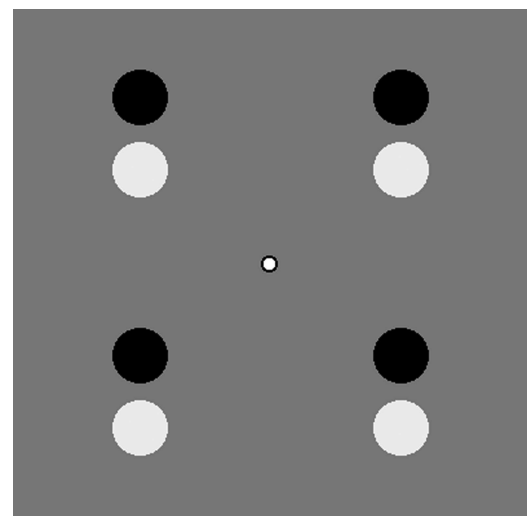
Movie 2. Two pairs of white spots, and two pairs of black spots, tend to move locally, which demonstrates that spots of the same polarity tend to be perceptually grouped together.

adaptation to visual motion presentations; local object spacing (proximity); similarity in object luminance; orientations of edge-defining contours and their motion trajectories.

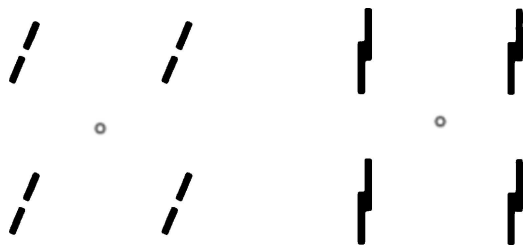
In our experiments we constructed displays of moving spots or lines that could be perceptually linked together in multiple ways. These ambiguous motion displays (see [Movies 1–8](#)) can be interpreted either as local motion occurring at small parts of the display, or as global motion occurring across the whole display. We first examine the effects of object density, luminance, and



Movie 1. The four dot pairs are at first perceived as four locally spinning objects, but then coalesce to appear as two globally circling squares.



Movie 3. Four piebald pairs of spots tend to move globally, which demonstrates that spots of the same polarity tend to be perceptually grouped together.

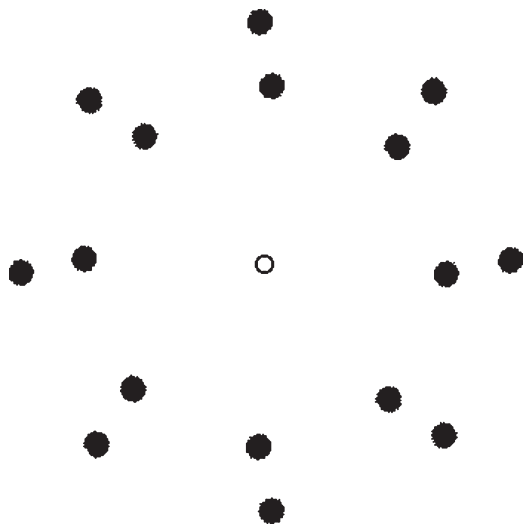


Movie 4. Radii tend to move locally, but floating verticals tend to move globally, which suggests that the visual system prefers rigid motions.

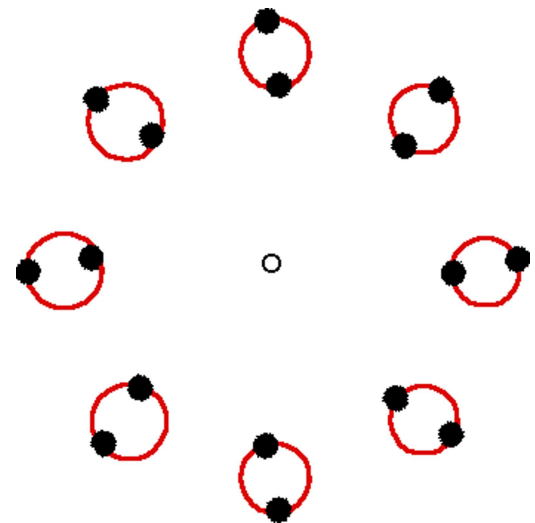
orientation of moving visual features on perceived local and global motion. Later, we assess the effect of high-level information on the formation of local and global motion percepts.

## Experiment 1: Probability of seeing local vs. global motion as a function of time, within and across trials

The basic building block of our display was a pair of spots rotating around their common center at 1 rev/s, which we refer to as a doublet. Seen on its own, its rotation is clear and unambiguous. Four doublets arranged in a square formation look at first like four local rotations. But after some seconds the display suddenly appears to change radically, even though nothing actually changes on the screen. Now, instead of four small, independently rotating doublets, the spots coalesce into the percept of



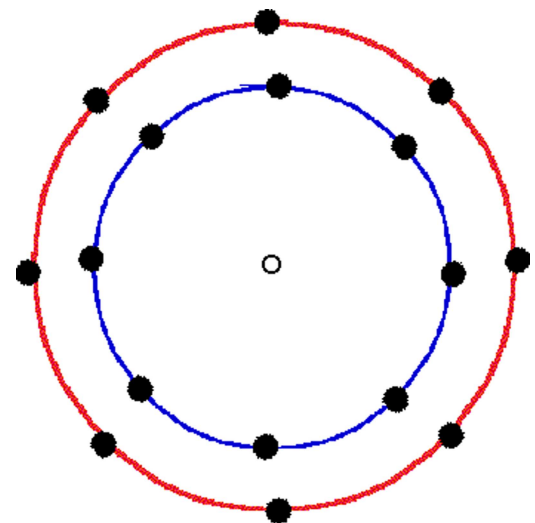
Movie 5. The eight pairs of spinning spots are seen either locally as eight spinning objects, or else globally as two intertwining octagons.



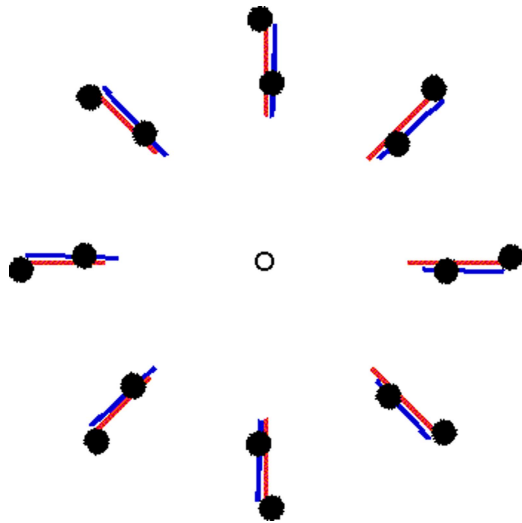
Movie 6. Small static circles define the local motion trajectories from the previous movie. Spots are always seen as spinning locally.

two large squares sliding over each other. Each square contains one spot from each doublet. These large squares appear as robust coplanar objects that move along circular paths without deforming or rotating, somewhat like a sponge in the hand of a window cleaner. Thus, the observer sees four small pairs of rotating spots when perceiving local motion, and two large quartets of spots following circular paths when perceiving global motion.

In [Experiment 1](#), we measured the time course of alternations between local and global motion percepts. The number of dots populating each local group was varied, as was the number of local groups presented on the display. We predicted that adding more independent groups would increase global motion coherence, which should sustain the onset of perceived global motion.



Movie 7. Large expanding and contracting circles constrain the motion to look like two global octagons.



Movie 8. Oscillating radii are also seen to favor global motion.

Increasing the population size of local groups was expected to reduce the likelihood of perceived global motion, as the greater number of coherently moving visual features would define the edges of local disks as opposed to the edges of individual global shapes.

## Method

### Observers

Ten naive undergraduate psychology students recruited from the University of California San Diego (USCD) with normal or corrected-to-normal vision participated in the experiment for course credit.

### Stimulus

The basic stimulus comprised pairs of  $0.5^\circ$  diam. black spots, separated by  $2.5^\circ$  (Movie 1). Each pair rotated about their common center at 1 rev/s, as though they were mounted on the rim of an imaginary disk  $2.5^\circ$  in diameter. Four such spot pairs rotated in synchrony. Each spot pair had a mean eccentricity of  $8^\circ$  and was positioned at one corner of an imaginary square with  $11^\circ$  side lengths. A fixation point at the square's center was used to maintain the observer's gaze on the display.

In addition to spot pairs ( $180^\circ$  separation), we examined the effect of triplets ( $120^\circ$  separation) and quartets ( $90^\circ$  separation) of local spots (not shown) on perceived local and global motion. These displays comprised two, three or four spots, equally spaced around the circumference of an imaginary disk of diameter  $2.5^\circ$  and rotating about their common center. We also varied the number of groups of spots (doublets or triplets or quartets) that were displayed. On some trials we used four groups of spots, arranged as before at the corners of an imaginary square. On other trials we presented fewer groups by erasing one or two

randomly chosen group(s). Removal of two groups occurred on adjacent or on diagonally opposite corners of the imaginary square. So our nine conditions were as follows:

4 doublets, 3 doublets, 2 doublets

4 triplets, 3 triplets, 2 triplets

4 quartets, 3 quartets, 2 quartets

The stimuli used in these conditions are diagrammed as icons, not to scale, in Figure 2a. Stimuli were presented on a 24" iMac LCD monitor (luminance range:  $\sim 1.0$  cd/m<sup>2</sup> to 133.0 cd/m<sup>2</sup>).

### Procedure

Observers were instructed to fixate the center of the motion display for a period of 30 s, and to press keys on a keyboard to indicate when they saw local motion of (say) four small spot pairs, or global motion of (say) two large four-spot groups. No practice trials were given, but observers were provided with information about what to expect when seeing local or global motion (i.e., a large shape or independent groups of rotating spots). The time intervals for which each interpretation persisted were recorded and analyzed offline. This procedure was repeated ten times for each observer, with brief rests between trials.

## Results and discussion

Figures 2b and 2c show two representative samples of the nine conditions plotted as graphs. Figure 2b shows that global motion became more prevalent over the course of a 30 s trial (mean of 10 trials  $\times$  10 observers), steeply rising at first and then leveling out. Four doublets always gave rise to more global motion than four triplets. Figure 2c re-plots the same data to show that global motion also increased across a series of ten trials, and again four doublets always produced more global motion than four triplets. These results could relate to processes of learning and adaptation, both tending to favor global motion, but with different time constants: a short-term process (adaptation) operating within individual trials and a longer-term process (learning) operating across consecutive trials.

We determined the overall proportion of time that global motion was perceived in each trial to estimate the strength of perceived global motion in each condition. The 3D-bar graph in Figure 2d shows the average portion of time global motion was reported across all trials and all observers in each condition. Vertical bars represent separate conditions, as laid out in the schematic of Figure 2a, with the number of local groups running from

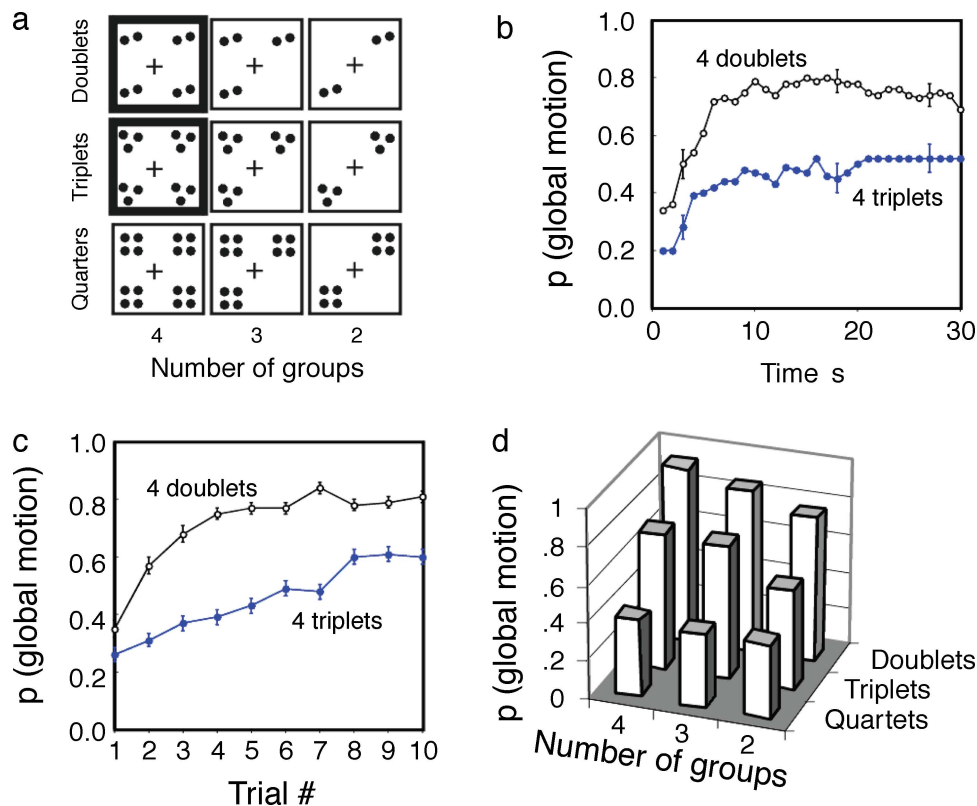


Figure 2. The configurations of moving spots used in [Experiment 1](#) (a). The center '+' shows the fixation point. Groups of two (doublets), three (triplets) or four (quartets) spots rotated about their common centers peripheral to fixation. The number of local groups also varied between two, three or four as shown. Probabilities of observers seeing global motion as a function of time in seconds (b) or trial sequence (c) are shown for the conditions with four doublets and triplets (diagrams with bold outlines in a). Mean probability across all conditions provided in (a) are represented in a 3D bar graph (d).

right to left and the number of spots in each group running from far to near. The 3D graph shows that increasing the number of groups increased global motion, but increasing the number of spots within each group reduced global motion. We conjecture that increasing the number of groups adds to the sampling evidence for perceiving global motion, as global squares subsume more stimulus evidence than global triangles. However, increasing the number of spots per group may make global motion harder to perceive, because four overlapping global squares are harder to disentangle than two or three. Also, increases in local spot density may increase the number and strength of perceived local connections, reducing the likelihood of forming global motion percepts.

## Experiment 2: Separation and luminance polarity of spots

In [Experiment 1](#), we found that increasing local group sizes sustained perceived local motion and delayed the onset of perceived global motion. The addition of more

dots to a group would have reduced the arc distance between adjacent dots rotating around a common point. This may have enhanced local grouping due to proximity, which strengthened local connections and thereby increased perceived local motion. If so, then increasing the diameter of local group motions should weaken these local connections and facilitate global motion perception. In [Experiment 2](#), we titrated the threshold of separation, or point of subjective equality (PSE), at which local and global motion percepts were equi-probable. We also explored the possible role of grouping on the basis of similarity by coloring the spots in ways expected to favor either local or global motion. We predicted that the perceptual bonds for global motion would be stronger when individual global shapes comprised spots of the same rather than opposite luminance polarities.

## Method

### Observers

Thirteen naïve post-graduate psychology students recruited from the University of Sydney with normal or corrected-to-normal vision participated in the experiment.



## Stimulus

Four doublets (pairs of spots) were arranged at the corners of an imaginary square, and rotated in step at 1 rev/s on a mid-gray surround. Each doublet had an eccentricity of 4.5°. In condition 1, intended to favor global motion, each doublet comprised one black spot and one white spot (Movie 3). In conditions 2 and 3, which were controls, the spots were all white or all black. Condition 4 was intended to favor local motion at the expense of global motion, where the two doublets at diagonally opposite corners of the square were white, and the two doublets along the other diagonal were black (Movie 2). In this condition, a large perceptual square would contain two black and two white spots, and could not be perceived on the basis of similarity in luminance. If similarity in luminance polarity is an important grouping cue in these displays, then four spots of the same luminance polarity should be readily grouped to form a globally perceived square.

## Procedure

One practice trial with unipolar black or white spots was given at the start of the experiment, where observers were explicitly shown the two possible perceptual states of global squares and local disks. The observer controlled the separation between the two spots within each doublet with a staircase method. If the observer saw local motion, s/he hit one designated key, which moved the spots within each doublet further apart to favor global motion. If s/he saw global motion, s/he hit a second key, which moved the spots within each doublet closer together to favor local motion. Thus the spot separations on each key press depended upon the observer's report on the previous key press. This negative-feedback procedure homed in on the separation threshold at which local and global motion percepts were equally likely. Conditions were run in random order, with at least three trials per condition and each trial lasting 30 s. Results were recorded for later analysis. We took the mean of the last four reversals in each staircase as our estimate of the spot separation threshold (i.e., the PSE) for each observer in the four conditions.

## Results and discussion

In short, we titrated the spot separations to vary the strength of the perceptual glues that stuck spots together either locally or globally, and we found that spots of similar luminance polarities tended to stick together. These results are shown in Figure 3, with thumbnails of the stimuli along the horizontal axis. The vertical axis shows the PSE of the spot separation (in degrees) at which local and global motion percepts were equally probable.

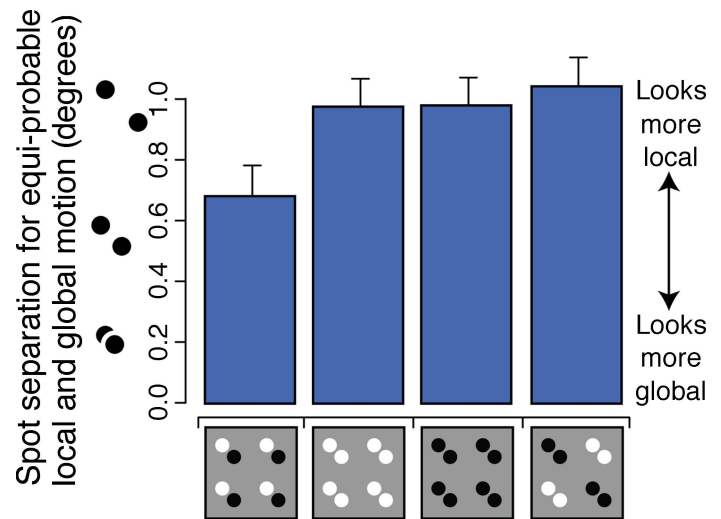


Figure 3. Means and standard errors showing spot separation where local and global motion percepts were equi-probable. Compared to conditions with all white spots or all black spots (bars #2 and #3) global motion was more likely to be perceived when each doublet contained one white and one black spot (bar #1) and less likely when two white doublets and two black doublets were used (bar #4). This demonstrates that spots of the same luminance polarity tend to appear to move together.

A repeated-measures one-way ANOVA performed on these PSE data was found to be significant ( $F_{3,36} = 9.14$ ,  $p < 0.0005$ ). In the control conditions (second and third vertical bars in Figure 3), the spots were all white or all black, favoring neither local nor global motion. There was no statistical difference in the mean PSE across these two conditions ( $t_{12} = 0.13$ ,  $p = 0.90$ ), so the data scores for each observer were averaged to obtain a stable estimate of the PSE obtained with unipolar spots ( $M = 0.98$  deg,  $SD = 0.33$ ). When two doublets were white and two were black (right-most bar in Figure 3), local motion was seen more often, and the mean PSE for these mixed polarity doublets ( $M = 1.04$  deg,  $SD = 0.34$ ) was significantly greater than the PSE obtained with unipolar spots ( $t_{12} = 2.63$ ,  $p < 0.05$ ). Finally, when each doublet contained one black and one white spot, global motion was seen more often and the PSE fell to a lower mean separation ( $M = 0.68$  deg,  $SD = 0.36$ ). This was significantly smaller than for either the unipolar control stimulus ( $t_{12} = 2.70$ ,  $p < 0.05$ ) or the mixed polarity doublets ( $t_{12} = 3.52$ ,  $p < 0.005$ ).

Thus, as predicted, spots of the same luminance polarity (black or white) tended to be perceptually grouped together. Global motion was favored over local motion depending on how the black and white spots were spatially arranged in the display. The dependence of global motion on spot polarity is consistent with McDermott et al.'s (2001, 2004) studies on motion transparency. These authors found that simple line segments that were similar in luminance tended to cohere together in motion. Similar

effects may be at work in the experiment reported here, so we examine the role of similarity in feature orientation on perceived global motion in the next experiment.

### Experiment 3: Orientation of moving lines

The previous experiment showed that changing the luminance polarity of moving spots influences the perception of local versus global motion. Spots of the same polarity tend to be perceptually grouped together. Kohler, Caplovitz, and Tse (2009) have also assessed global motion percepts formed from local L-shapes that always remained upright in orientation. They found that the speed of global squares appear to move slower than the rotation of the L-shaped doublets. It is possible that global motion percepts may depend on similarity in orientation among locally distributed elements in the display. In [Experiment 3](#) we replaced the dots with dashes (i.e., oriented line segments). We examined whether similarity in dash orientation can facilitate grouping to produce biases in perceived local versus global motion.

## Method

### Observers

Six naive adults recruited from the University of Sydney with normal or corrected-to-normal vision participated in the experiment.

### Procedure

The control condition used four doublets, arranged at the four corners of a square of side  $9^\circ$ . This gave each doublet an eccentricity of  $6.5^\circ$  ( $=9 \times .707$ ). Each doublet comprised two black spots of diameter  $0.8^\circ$  and separation of  $1.3^\circ$  between centers. The doublets rotated at 0.53 rev/s for 30 s per trial. Four additional experimental conditions were constructed, where the black spots were replaced by short black lines,  $1^\circ$  long  $\times$   $0.3^\circ$  wide, still separated by  $1.3^\circ$  between centers ([Movie 4](#)). The lines were oriented in four different ways: radial, tangential, vertical and horizontal, as shown in [Figure 4](#). Radial lines pointed toward the center of local rotation. Tangents were laid along the circumference of each doublet. Horizontal and vertical lines always remained parallel to one another.

One practice trial with unipolar white spots was given at the start of the experiment, where observers were explicitly shown the two possible perceptual states of global squares and local disks. As before, observers hit two keys to indicate when the motion appeared global or local. The times of individual key presses were recorded for later analysis; but note that in this experiment, the spot

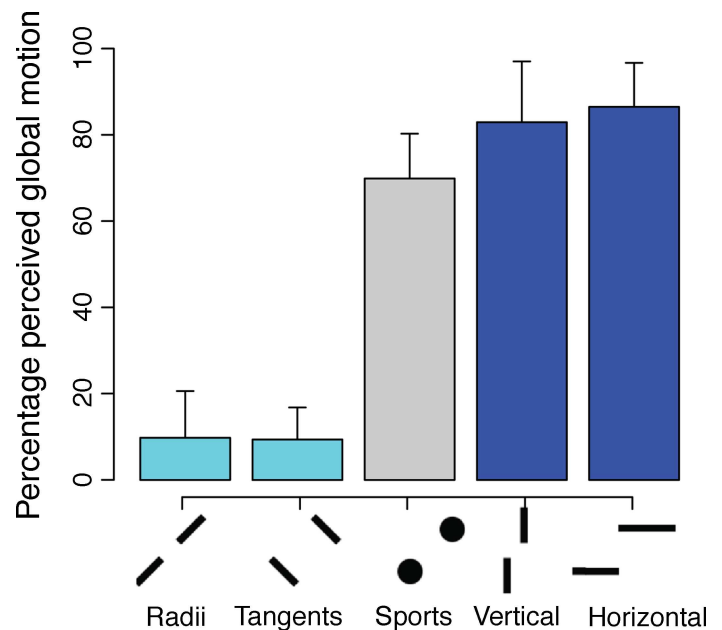


Figure 4. Means and 95% confidence intervals showing percentage of total time visual motion was judged to be global. This was lower for radii and tangents, compared to floating lines that remained vertical or horizontal as they rotated. Rotating spots were judged as global motion more often than radii and tangents, but slightly less often than parallel lines.

separations were fixed and were not changed by striking the keys. The portion of time for which perceived global motion was reported was averaged over a total of five 30 s trials per condition.

## Results and discussion

The bar graph in [Figure 4](#) shows the average percentage of time global motion was perceived in the five conditions. Conditions with short radial or tangential lines (light blue bars in [Figure 4](#)) tended to favor local motion. In these conditions, global motion predominated for only 9.8% of the time with radial segments ( $SD = 12.7$ ) and only 9.4% of the time with tangents ( $SD = 13.5$ ). There were no significant differences in perceived global motion between these two conditions, as indicated by a repeated-measure t test ( $t_5 = 0.12$ ,  $p = 0.91$ ). In comparison, the control condition with rotating spots (gray bar in [Figure 4](#)) appeared to move globally for approximately 69.8% of the time ( $SD = 12.9$ ).

The conditions with floating horizontal or vertical lines (dark blue bars in [Figure 4](#)) tended to favor global motion. The horizontal line segments favored global motion for 82.8% of the time ( $SD = 17.6$ ) and the vertical line segments favored global motion for 86.4% of the time ( $SD = 12.7$ ). There were no significant differences in perceived global motion between these two conditions, as

indicated by a repeated-measures *t* test ( $t_5 = 1.08$ ,  $p = 0.33$ ). However, in comparison to the control condition with spots, repeated-measures *t* tests showed that a greater percentage of global motion was perceived with both horizontal floating segments ( $t_5 = 3.20$ ,  $p < 0.05$ ) and vertical floating segments ( $t_5 = 4.03$ ,  $p < 0.05$ ).

The finding that tangential and radially rotating stimuli were perceived more often as local motion may relate to their perceived rigidity. When the tangents or radii rotated, they appeared to move rigidly as though the lines were painted upon a small invisible rotating disk. They appeared to move non-rigidly when they were seen as two large moving squares. However, floating horizontal or vertical lines lying along the sides of these squares appeared as large rigid squares that translated over each other along circular paths. These features shear non-rigidly at the local level, limiting the generation of perceived local motion. This is consistent with the idea that the visual system prefers rigid motion (Hildreth, 1984; Ullman, 1979), free of any shearing. It seems that the visual system constructs a transparent rotating surface for each doublet, on which the constituent lines appear to attach. This could reflect an involvement of high-level information driving one percept over another, which we consider further in the next experiment.

## Experiment 4: Phase shifts between doublets

In Experiments 1 to 3, all rotations were synchronized in phase (i.e., kept in step). These rotations generated percepts of global or local motion depending on the luminance polarity of moving spots and the orientation of moving line segments. The dependence of perceived global motion on the specific orientation of globally distributed moving features may suggest that a high-level visual process underlies the perception of global motion. The perceptual process involved in global motion perception may be consistent with high-level visual processes implicated in the perception of motion transparency in previous research (McOwan & Johnston, 1996).

In Experiment 4 we introduced progressive phase shifts between adjacent doublets. These shifts did not affect individual local motions but they were found to impart a waviness to global motions. We also added static or moving lines (or “guide paths”) that delineated the possible trajectories, either local or global. If a high-level process underlies the perceptual strength of global versus local motion, then the addition of these guide path trajectories should influence the perceptual organization of moving features in the display. Therefore, we expected that adding guide paths should strongly bias the perceptual strength of perceived global versus local motion.

## Method

### Observers

Four naive undergraduate psychology students recruited from the University of California San Diego (USCD) with normal or corrected-to-normal vision participated in the experiment.

### Stimuli

Eight rotating doublets arranged in a circle were each phase-shifted by  $45^\circ$  from their neighbors, so that at one instant they were all radial with the axes of the doublets pointing toward the center of the circle. One-quarter cycle later they were all tangential and lay around the circumference of an imaginary circle. In between these times they conformed to a time-varying spiral. The local motion percept was of eight doublets rotating in different phases, while the global motion percept was an intriguing pair of interlaced octagons that oscillated and changed sizes as they snaked around each other.

We superimposed guide paths in the form of various red lines on the spots and examined their effects. These comprised: (i) a control condition with bare spots and no red lines (Movie 5); (ii) small static circles of the same diameter as the circular paths the doublets moved along (Movie 6); (iii) large expanding and contracting circles that passed through the two global circles of spots (Movie 7); (iv) large oscillating radii that also passed through the two global circles of spots. Stimuli were presented on the same iMac display used in Experiment 1.

### Procedure

No practice trials were given, but observers were informed that there would be two possible percepts: large octagons or eight groups of rotating spots. Observers were instructed to strike keys to indicate when they saw local or global motion, over a series of three 30 s trials. Striking the appropriate keys did not alter the display in any way. Responses were recorded, and the total proportion of time that global motion was reported was averaged across all observers and all trials per condition.

## Results and discussion

Mean probabilities  $\pm 1$  SEM of seeing global motion are shown in the bar graph of Figure 5. A repeated-measures one-way ANOVA performed on these data was found to be significant ( $F_{3,27} = 17.84$ ,  $p < 0.00005$ ). In the control condition with no superimposed lines (bar #1 in Figure 5), the global snaking octagons were perceived for 51% of the time ( $SD = 16.7$ ). Displays with small static circles added to them (bar #2 in Figure 5) were found to favor local motion. These small circles significantly reduced the



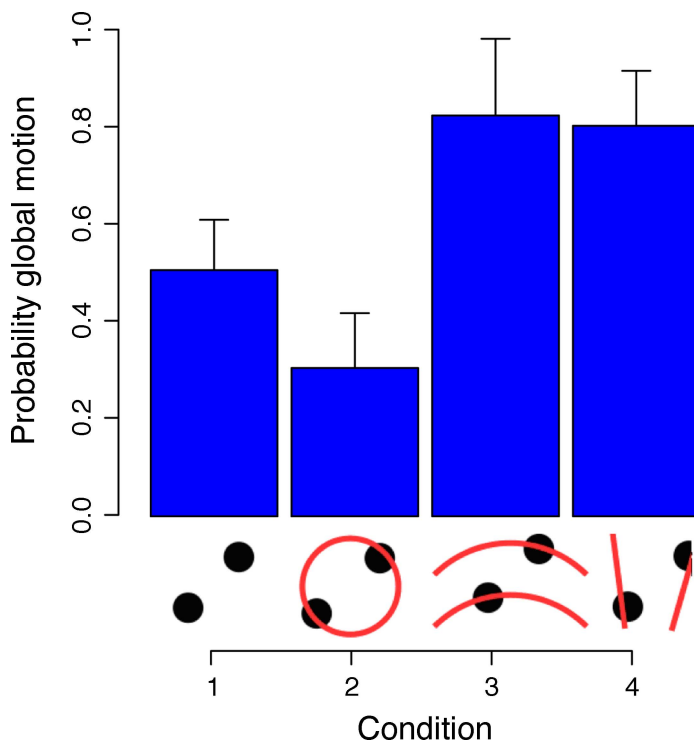


Figure 5. Means and 95% confidence intervals showing probabilities of perceiving global motion. Eight phase-shifted circling doublets give a global percept of interleaved octagons snaking through each other (Condition 1). This global effect was sharply reduced when each doublet had a small static circle superimposed (Condition 2). Global motion was increased by large moving circles or radii that emphasized the global trajectories (Conditions 3 & 4).

duration of perceived global motion to only 30% of the viewing time ( $SD = 18.2$ ), as indicated by a repeated-measures  $t$  test ( $t_9 = 2.33$ ,  $p = 0.04$ ). Observers also informally noted that adding the static circles made the local motion appear ‘calmer’ and smaller in amplitude.

In comparison to conditions with small circles, adding large expanding and contracting circles (bar #3) and oscillating radii (bar #4) increased the durations of perceived global motion to 82% ( $SD = 25.4$ ) and 80% ( $SD = 18.2$ ) respectively. Both these differences were found to be significantly greater than the control condition according to repeated-measures  $t$ -tests ( $t_9 = 4.54$ ,  $p < 0.005$ , and  $t_9 = 4.09$ ,  $p = 0.005$ , respectively). These data show that adding simple contours to the display provided explicit ‘guide paths’ that strongly influenced the perceived trajectories of the ambiguous spots.

## General discussion

In this study we presented ambiguous motion displays and found that altering specific stimulus parameters biased

percepts of local and global motion. These parameters included the proximity, number, and similarity of the moving elements. In terms of *proximity*, we found that putting the spots closer together within a doublet strengthened local as opposed to global motion. Putting the doublets further apart strengthened global as opposed to local motion. In terms of *numbers*, increasing the number of doublets enhanced global motion, whereas increasing the number of spots within each local cluster from two (as in a doublet) to three or more enhanced local motion. It is possible that adding spots to a cluster simultaneously increases the evidence that the cluster is an independent object, and also makes it harder to disentangle global shapes; three or four overlapping large squares are harder to make out than two. In terms of *similarity*, when half the spots were luminance increments and the other half were luminance decrements, we found that observers tended to link spots of the same polarity together. Doublets comprising two black spots or two white spots tended to move locally, but if doublets contained one black and one white spot, so that same-polarity spots were distributed across different doublets, this enhanced the global motion across doublets.

What was true for the polarity of spots was also true for the orientation of dashes (short lines). Doublets comprising two radial or two tangential dashes tended to move locally, since the orientation of the short lines rotated in step with the rotary local motion. But doublets comprising two ‘floating’ lines that remained vertical or horizontal, like north-seeking compass needles, enhanced the global percept of large translating squares. Here the orientations of the lines did not rotate but stayed upright, always remaining parallel to the sides of the global squares.

The point here is that observers showed a strong preference for rigid rather than non-rigid motion. Radial and tangential lines appeared to rotate locally as though they were painted on small, invisible, rigidly rotating disks. The radii and tangents were rarely perceived as globally translating squares, since such squares would shear continuously at their corners. Conversely, the floating vertical or horizontal lines were parallel to the sides of the large squares, which had rigid global motions and hence were perceptually preferred. The two vertical or horizontal lines within a doublet moved non-rigidly, shearing continuously past each other and rarely generating percepts of local motion. This is consistent with the rigidity constraints in motion perception that have been discussed previously (Hildreth, 1984; Ullman, 1979).

The cues that make moving spots group together can be compared to the well-known Gestalt cues that make static spots group together (Koehler, 1969). Spot similarity and proximity both influence grouping of static and moving spots. Numerosity is a doubtful case; increasing the number of spots within doublets, or increasing the number of doublets, enhance local and global motion respectively. It is not clear that this would apply to groups of static spots. The rigidity constraint is purely a motion cue that

does not apply to static shapes at all, but was found to strongly affect perceived local versus global motion with oriented moving dashes in [Experiment 3](#). Both local and global groupings depend upon the Gestalt notion of “common fate” (Koehler, 1969) but the different spot groups have different kinds of motion in common. The local members of a doublet share common rotation about a central point, and the global members of a large circling square share parallel paths of translation. Since common fate describes both, it alone cannot explain the differences between them.

Local and global motion percepts are two different and antagonistic solutions to a binding problem, namely binding spots into groups. They are antagonistic because it is impossible to see the same spots as partaking in local and global groups simultaneously. We can think of them as “motion objects” undergoing different forms of figure/ground segregation. These perceived shapes appear to be segregated using processes prone to adaptation (and learning), and possibly visual attention.

### ***Adaptation and the time course of local–global motion alternations***

The temporal alternation between local and global motion was *not* like the alternations of a Necker cube, nor like the switching between eyes during binocular rivalry. De Marco et al. (1977) and Leopold and Logothetis (1999) have measured the distribution of time intervals for which percepts were dominated by each rivaling eye’s image or each depth configuration of the Necker cube. Binocular rivalry and Necker cubes both generate a gamma distribution among perceptual alternations, conforming to the probability density for summing the events of a Poisson process. This would be expected if the perceptual alternation is driven by a stochastic process that has no memory; that is, if the duration of the  $n$ th interval does not help to predict the  $(n + 1)$ th interval. However, percepts adapted strongly within trials and showed retention in the form of perceptual learning across trials. For this reason, the perceptual alternation of local versus global motion appears to involve a processing mechanism that *does* have memory of a kind.

### ***The role of high-level processes and attention***

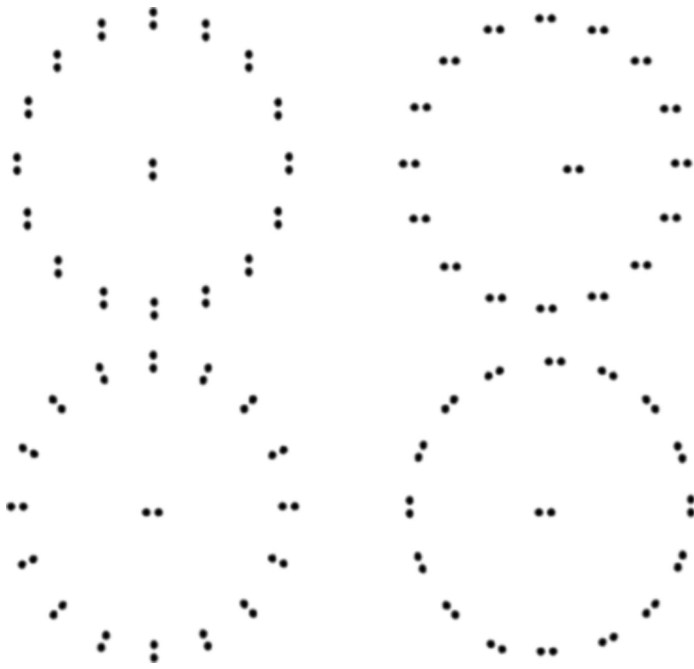
Nearby spots that move along common or similar paths are organized immediately into local motion groupings, which may be driven by a pre-attentive process. One possibility is that global motion perception involves an initial attentive tracking of the moving spots (Cavanagh, 1992; Culham et al., 1998), followed by a perceptual grouping of remote spots on the basis of their parallel motion paths.

Chang and Troje (2009) suggest that the perception of biological motion in point-light walkers is sub-served by

both a global process that retrieves structural information and a local process that is sensitive to individual limb motions. They concluded that these global and local kinds of information are processed by two distinct neural mechanisms. Navon (1977, 1983) showed that when patients with a lesion to the left hemisphere view [Figure 1b](#), they tend to perceive the large global N, while patients with a lesion to the right hemisphere tend to report the small local S’s. This suggests that the left hemisphere may be specialized to see the trees, the right hemisphere to see the forest. This cortical specialization could relate to the involvement of a high-level attentive process.

Raymond (2000) has reviewed the modulation of global visual motion perception by attention. Consistent with earlier researchers (Ullman, 1979), she concluded that there are probably two levels of motion processing, a motion data level and an object-relevant level. The motion data level, primarily involving V1, uses image filtering mechanisms to extract motion signals from information in the stimulus. This level has been generally viewed as a purely stimulus-driven filtering process, uncomplicated by the processes responsive to task relevance (Adelson & Bergen, 1985; van Santen & Sperling, 1985). The object-relevant level is needed to account for motion perception of complex stimuli, such as our own ambiguous displays which contain multiple motion vectors. This level may segment and integrate information collected from the motion data level into discrete object representations (Lu & Sperling, 1995; Qian et al., 1994; Raymond, 2000; Valdes-Sosa, Bobes, Rodriguez, & Pinilla, 1998).

It is possible that a similar high-level attentive mechanism may integrate segmented local motions over time into percepts of motion transparency. McOwan and Johnston’s (1996) experiments are consistent with the results in our [Experiments 1](#) and [2](#). They found that an array of  $12 \times 12$  closely packed doublets generated percepts of ‘motion transparency’, equivalent to our ‘global motion’. When they increased the number of spots in each doublet to four, producing a  $12 \times 12$  matrix of quartets, they now observed ‘rotations’, equivalent to our ‘local motion’. These results are consistent with our numerosity results in [Experiment 1](#) with edge-defined local and global motion. We extended these observations to show that spacing of features within local groups increases the strength of perceived global motion. However, McOwan & Johnston still obtained local rotations when each quartet in the matrix contained two black and two white spots, the opposite of our polarity results in [Experiment 2](#). It is possible that this difference may relate to the emphasis on surface-defined global motion, as opposed to edge-defined global motion as in our study. Consistent with the view that edge-defined motion facilitates segmentation and grouping, we found that global motion percepts only occurred when the orientation of luminance-defined features formed rigid edge contours of globally moving surfaces.



Movie 9. Global motion percepts are still formed with counter-phase translating local spots defining the edge contours of global shapes.

Regardless of whether attention plays a major role in global motion perception, it appears that segregation and grouping for global motion perception do not depend on differences in the rotational and translational trajectories of our locally moving spots. In our study, local motion was defined by the rotation of local disks, whereas global motion was defined by the translation of large shapes. In [Movie 9](#), we arranged 16 doublets in a circle, which expand and contract in phase. That is, the separation between the two dots increase and decrease rhythmically among all the doublets together. The direction of the resulting global motion is seen to depend entirely upon the orientation of the doublets. When all the doublets are oriented vertically (or horizontally), one sees two overlapping circles of the same size, moving up and down (or left and right) in counterphase. When the doublets are arranged radially, with all their axes pointing toward the center of the circle, one sees two concentric circles of different sizes, with the inner circle becoming smaller as the outer circle becomes larger. Finally, when the doublets are arranged tangentially—all lying around the circumference of the circle—one sees a single circle that pulsates without changing in size or position.

The effect of similarity in luminance polarity on perceived global motion ([Experiment 2](#)) does not appear to depend on the similarity in contrast sign of the moving spots. The animated gif icon accompanying this paper shows that the percept of global motion dominates when one of the dark spots in each doublet suddenly changes in luminance to mid gray against the white background.

Because contrast sign is preserved between the two overlapping global squares, it appears that similarity in luminance, rather than contrast sign, mediates the grouping of spots into separately perceived global shapes.

In our view, the grouping of moving spots into local motion clusters is an early, fast, pre-attentive event, while grouping them into global motion clusters is a slower, high-level process. Both percepts appear to involve an object-relevant level producing different kinds of “motion objects”, namely small local doublets (triplets or quartets) and large, global squares. We envisage a preliminary linking up of nearest neighbors as a tentative motion hypothesis, followed by a slower, spatially wider search for more global correspondences. In particular, we regard global motion as a higher level of perceptual organization than local, since like any good scientific theory, it groups the maximum amount of evidence (spots) into the minimum number of perceptual hypotheses (global groups), thus combining generality with parsimony. Reverting to our cheetah example, it is a modest visual achievement to group some of the moving spots locally into legs or a tail, but a prey’s actions and survival will ultimately depend on organizing them globally into the percept of a whole cheetah.

Additional relevant resources and demonstrations can be seen on the lead author’s web page at: [www-psy.ucsd.edu/~sanstis/demos](http://www-psy.ucsd.edu/~sanstis/demos).

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