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The "motion silencing" illusion results from global motion and crowding

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Suchow and Alvarez (2011) recently devised a striking illusion, where objects changing in color, luminance, size, or shape appear to stop changing when they move. They refer to the illusion as "motion silencing of awareness to visual change." Here we present evidence that the illusion results from two perceptual processes: *global motion* and *crowding*. We adapted Suchow and Alvarez's stimulus to three concentric rings of dots, a central ring of "target dots" flanked on either side by similarly moving flanker dots. Subjects had to identify in which of two presentations the target dots were continuously changing (sinusoidally) in size, as distinct from the other interval in which size was constant. The results show: (a) Motion silencing depends on target speed, with a threshold around 0.2 rotations per second (corresponding to about 10°/s linear motion). (b) Silencing depends on both target-flanker spacing and eccentricity, with critical spacing about half eccentricity, consistent with Bouma's law. (c) The critical spacing was independent of stimulus size, again consistent with Bouma's law. (d) Critical spacing depended strongly on contrast polarity. All results imply that the "motion silencing" illusion may result from crowding.

Introduction

Suchow and Alvarez (2011) have described a stunning new illusion, winning the Vision Sciences Society's "Best Illusion of the Year Contest" in 2011. They display a field of different colored dots, each continuously cycling through the color spectrum: When the pattern is stationary, the changes in color are extremely salient; however, when the dots are rotated smoothly, the sense of color change is immediately lost. Only by tracking a single dot can we check that the colors are still changing. Not only were changes in color imperceptible, but also changes in size, luminance, and shape (see demonstrations in Supplementary Movie S1).

This is not the first dramatic demonstration that much detail of visual scenes escapes our awareness. Perhaps the clearest demonstrations are the many examples of "change blindness" (O'Regan, Rensink, & Clark, 1999; Pashler, 1988; Rensink, O'Regan, & Clark, 1997; Simons, 1996), where major changes in a scene (such as the removal of an airplane engine) go completely unnoticed if the transient signals are masked by luminance transients or "mud splashes." However, in these demonstrations, attention to the region of space where the change occurs usually foils the effect, where "motion silencing" seems to resist attention to individual dots.

Suchow and Alvarez (2011) performed a series of experiments to understand the mechanisms behind the phenomenon. For example, they showed that it is motion on the retina, rather than in space, that is important for the silencing (readily verified by tracking a single dot). They also showed that "temporal freezing" (not updating information about the color of the dots) cannot explain the effect. However, the explanation for this dramatic effect remains illusive.

In a commentary accompanying Suchow and Alvarez's publication, one of us (Burr, 2011) suggested that the effect rests on two causes: global motion and crowding. The processes of global motion—in this case circular motion—could integrate the signals of transition state, effectively absorbing them (as in change blindness). Crowding acts to merge each dot with each other, creating a field of many colored dots without specific perception of which dot has which color at any given time.

The purpose of the present study is to test this hypothesis explicitly. If both motion and crowding are responsible for the illusion, specific predictions can be

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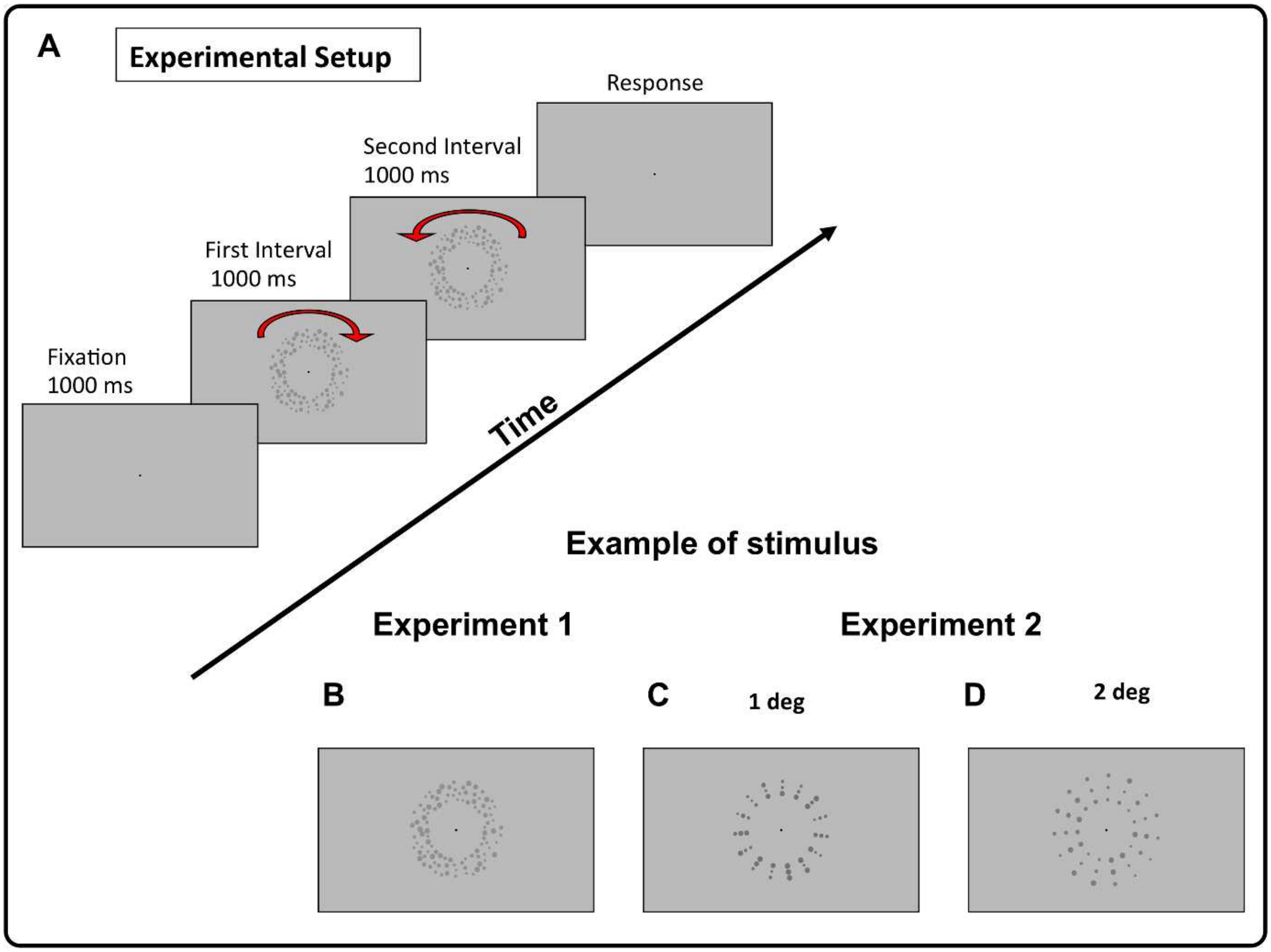

Figure 1. (A) Illustration of experimental conditions. Each trial began with fixation point for 1000 ms followed by two rotating clouds of 100 dots presented in two separate intervals lasting 1000 ms. (B) Illustration of the stimuli used in the first study. It comprised 100 size-changing dots positioned within an annulus of minimum 5° and maximum 8° radius. (C) Stimulus used in the crowing study: 45 dots, arranged in three concentric rings at radii 6°, 7°, and 8°. (D) Like the stimulus of C except the radii were 4°, 7°, and 10°.

made: The illusion should be highly dependent on velocity, and on the spacing of the dot stimuli. In particular, the minimal spacing for the illusion should follow Bouma's law, which determines crowding. The minimal spacing for the illusion should be dependent on eccentricity and contrast-polarity, but not on dot size. All the results support the suggestion that "motion silencing" results from a combination of motion and crowding.

Methods

Suchow and Alvarez (2011) demonstrated their effect with four separate stimuli features: color, size, luminance, and shape. For our study, we chose the version with size-changing stimuli, which are amenable to simple and precise control (Figure 1 and Supplementary Movies S2–S5). The stimuli were generally dark dots of 80% contrast, whose diameter was modulated sinusoidally over time at 1 Hz, from 0.3° to 0.75° (mean = 0.5°). The dots were displayed on a gray background within an annulus of 60 cd/m^2, and rotated at variable speeds. The initial size of each dot was determined by random starting phase.

We used a two-alternative forced-choice paradigm to demonstrate that motion effectively "silenced" the perception of changing size. A trial comprised two 1-s presentations of rotating dot-displays (separated by a 200 ms pause), first clockwise then counterclockwise. In one presentation (randomly first or second) the size of the dots was modulated, in the other each dot remained of fixed size (random) size. Subjects maintained fixation at center, and reported in which presentation the dots were size-modulated.

Stimuli were presented in a dimly lit room on a 23-inch Acer (LCD) monitor (Acer S231HL, China) with 1920 × 1080 resolution, at a refresh rate of 60 Hz,

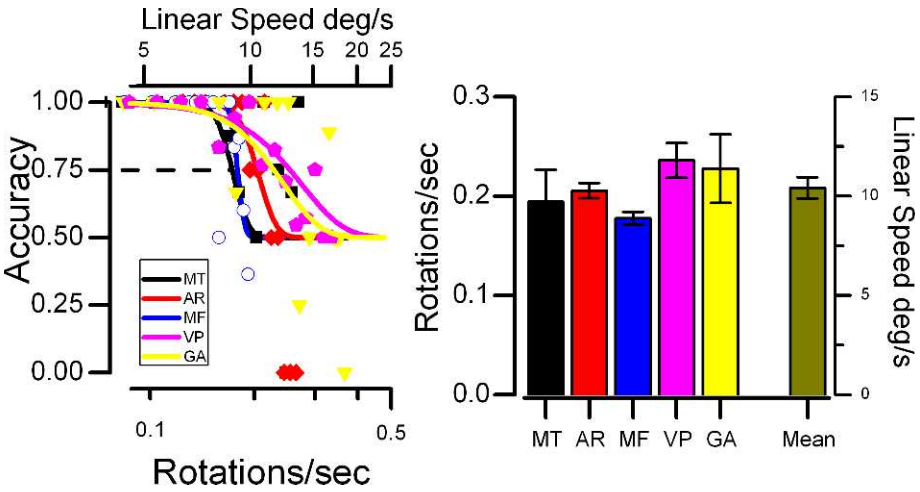

Figure 2. (A) Psychometric functions of the five subjects for judging the interval with the size-modulated stimuli, of the type shown in Figure 1B. (B) Thresholds (75% correct response) for each subject's mean speed threshold is around 0.2 rotations per second, corresponding to 10.5°/s average local linear speed. Error bars are ±1 *SEM*, calculated by bootstrap for individual subjects, and by traditional means for the mean.

viewed binocularly from 57 cm. Stimuli were generated and presented under Matlab 7.6 using PsychToolbox routines (Brainard, 1997) running on a Macintosh laptop (MacBookPro, Apple, Cupertino, CA).

In the first experiment, which established the validity of the method and measured motion thresholds, the stimuli were like those of Suchow and Alvarez: 100 dots scattered randomly within an annulus of minimum radius 5° and maximum 8°, with the constraint that no two dots overlapped (Figure 1A). The angular speed of rotation was varied from trial to trial, following the adaptive Quest algorithm (Watson & Pelli, 1983) to assess threshold speed for detecting the size change.

To study crowding, we arranged the dots in three concentric rings (see Figure 1, Supplementary Movies S3–S5), the central ring at 7°, and two flanking rings at variable distance from it. For most experiments the flanking dots were of the same contrast and polarity as the test dots (black, 80% contrast). In the last experiment, which studied the effect of contrast-polarity, the flankers could also be white, at 80% contrast. The procedure for all these studies was the same as for the initial experiment.

Five subjects participated in all experiments (mean age: 25 years, three male), all with normal or corrected-to-normal vision.

Results

Dependence on motion

The first experiment established the reliability of the measurement technique, and investigated the dependency of the effect on rotation speed. As described above, subjects were required to report in 2AFC the presentation where the dots were modulated in size. The angular speed of rotation varied from trial to trial, following the Quest algorithm.

Figure 2A shows psychometric curves for five observers, as a function of rotation speed. The curves are all orderly, showing that detection of the size modulation clearly depends on speed, and that subjects all perform in a similar manner. Panel B shows the 75% thresholds for the observers: In all cases, thresholds were similar, on average 0.21 rotations per second, corresponding to a linear speed of 10.5°/s. The strong and consistent dependency on speed shows the importance of motion for the silencing effect.

Dependence on crowding

Having established a viable forced-choice technique for measuring motion silencing, and demonstrating the dependency of the illusion on speed of rotation, we examined the crowding hypothesis. For this we simplified the stimuli to three concentric rings, with only the central ring of dots modulated in size. Again subjects identified the interval in which the central ring of dots was size-modulated.

We first measured motion thresholds with different distances between the flanking and central rings. Figure 3 reports speed thresholds (computed from psychometric functions like those of Figure 2A) for the three inter-ring distances. As predicted from the crowding hypothesis, thresholds varied monotonically with spacing from an average of 0.08 rotations per second

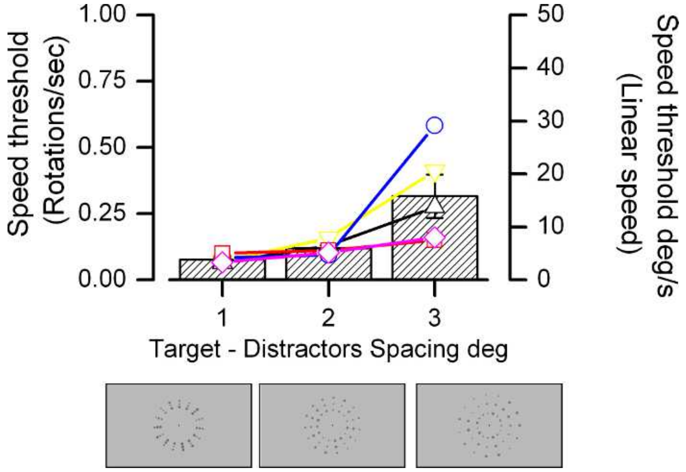

Figure 3. Speed thresholds as a function of separation of the rings of dots. Individual results color-coded as in Figure 2; average results indicated by the bars. Error bars are ±1 *SEM*. The icons below the abscissa show the layout of the stimuli.

(3.8°/s) for 1° spacing to 0.3 rotations per second (15 °/s) for 3° spacing.

The crowding hypothesis not only predicts that the silencing effect should depend on the closeness of the dots, but also predicts a clear threshold distance (Bouma's law). We therefore measured thresholds for critical spacing, using a fixed rotation speed of 0.21 rotations/s, near the speed threshold for the original stimulus (first experiment). Figure 4A shows thresholds for three different conditions: for large (average 1°) and small (average 0.5°) dots at 7° eccentricity and for small dots at 3.5° eccentricity. At 7° eccentricity, the threshold distance at which the size modulation was detectable 75% of the time was 3° (averaged across subjects). This corresponds to a Bouma constant (threshold distance divided by eccentricity) of 0.43 (Figure 4B), well within the range normally found in classical crowding studies. Importantly, thresholds did not vary with dot size, only with their spacing, again consistent with the crowding hypothesis.

We next varied the eccentricity of the rings, by changing viewing distance. This did affect thresholds, reducing the average from 3 to 2. This is qualitatively in agreement with the predictions of crowding. However, the Bouma constant in this condition is slightly higher than at the larger eccentricity, 0.55 rather than 0.43.

Finally we examined the effect of contrast polarity on critical spacing. The test dots were black (as before), and the distractor dots were either the same or opposite polarity (black or white). For this experiment we tested three subjects who had participated in the previous studies, plus two new naïve subjects. Figure 5 shows the results. For distractors of the same polarity, the threshold was 3.05°, similar to before, but for opposite-polarity distractors, the critical spacing was only 1.8°, significantly lower (paired *t* test, $p = 0.003$). The strong dependence on contrast-polarity is again consistent with crowding (Kooi, Toet, Tripathy, & Levi, 1994).

Discussion

This study provides firm support for the hypothesis that the silencing effect reported by Suchow and Alvarez (2011) resulted from a combination of motion integration and crowding. The effect clearly depends on motion, with a well-defined threshold. The motion threshold was 0.2 rotations per second (average linear

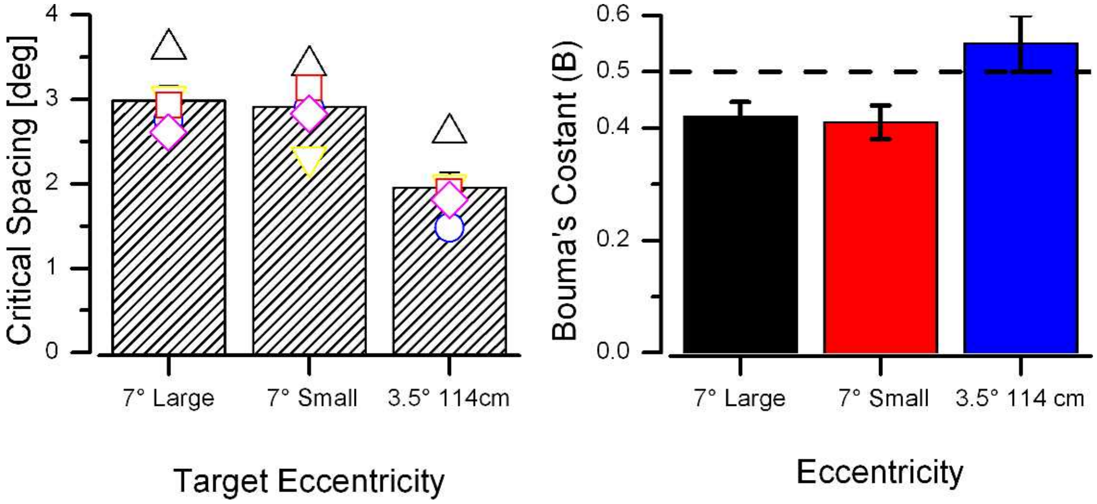

Figure 4. (A) Critical spacing between rings of dots under three different conditions: large and small stimuli (average size 1° and 0.5°) at 7° eccentricity, and small (0.5°) stimuli at 3.5° eccentricity. The 7° condition was viewed at 57 cm, the 3.5° condition at 114 cm. The symbols are individual results, color-coded as in Figure 2; the bars averages with errors showing ± 1 *SEM*. (B) Average Bouma constant (critical spacing divided by eccentricity) for the three experimental conditions.

speed around 10°/s) under the conditions used by Suchow and Alvarez. The motion thresholds varied with dot spacing, being much lower for closely spaced dots than broadly spaced, consistent with crowding. Thresholds for dot spacing were independent of dot size but depended on the spacing of their centers, as occurs with crowding (Bouma, 1970; Levi & Carney, 2009; Tripathy & Cavanagh, 2002). The Bouma constants for the silencing effects ranged between 0.4 and 0.6, well within the normal range reported in the literature (Pelli & Tillman, 2008; Whitney & Levi, 2011).

There is very good evidence that neural mechanisms integrate motion signals over large and complex trajectories. Neurons in the dorsal portion of area medial superior temporal area that respond specifically to various types of flow motion, including rotation, have very large receptive fields, often extending over more than 90° (Duffy & Wurtz, 1991; Tanaka & Saito, 1989; Tanaka, Fukada, & Saito, 1989). Psychophysical studies also show compulsory integration of flow motion (Morrone, Burr, & Vaina, 1995), again over very large areas (Burr, Morrone, & Vaina, 1998). It seems plausible that this integration process subsumes all dynamic signals within the area, including those associated with the changes in stimulus size.

There are several examples of global motion obscuring local motion, or transients. A field of coherently oriented dipole dot-pairs appearing continuously in random positions gives a strong impression of circular motion (Ross, Badcock, & Hayes, 2000; Supplementary Movie S6). So strong and smooth is the sense of motion that it is hard to believe that the dipoles in fact are appearing and disappearing at random. There is little sense of the dynamics of the individual dipoles; this is all consumed by the global sense of circular motion. A more mundane example is the "limited-lifetime" stimuli that most of us use routinely for motion studies. We are typically totally unaware that the dots continually drop out and reappear at random positions; yet if the display is stopped, the continuous flicker becomes obvious (Supplementary Movie S7). Saiki and Holcombe (2012) have provided an even more dramatic example of our inability to detect color changes in individual dots. Clouds of dots, half red and half green, rotating in an apparent sphere can all switch color, and the switch goes unnoticed, provided the summary statistics (such as red/green ratio) remain unchanged. This clearly shows that the visual system does not monitor independently the behavior of every single dot in multidot displays.

However, it is also clear that motion integration is not the entire solution. It is easy to track the changes in size (or other dimensions) in isolated or sparse arrays of dots in motion. One of the clearest examples is Boi, Ogmen, Krummenacher, Otto, and Herzog's (2009) demonstration of "nonretinotopic" processing, being able to process rotational motion in apparently moving objects, correctly with respect to the moving reference plane (Pooresmaeili, Cicchini, Morrone, & Burr, 2012). This is a more taxing problem than simply detecting that size or color has changed. Motion silencing also fails when the displays are sparse (see Supplementary Movie S5), leading to the suggestion that crowding may be involved. When the display is stationary, the dynamic change-signals of each element breaks through crowding, in the same way that temporal transients are known to cause 'pop-out,' reaching awareness without active attention; but if the signal-changes are subsumed by global motion mechanisms, then we would have to be able to individuate the dots to be able to detect changes in each.

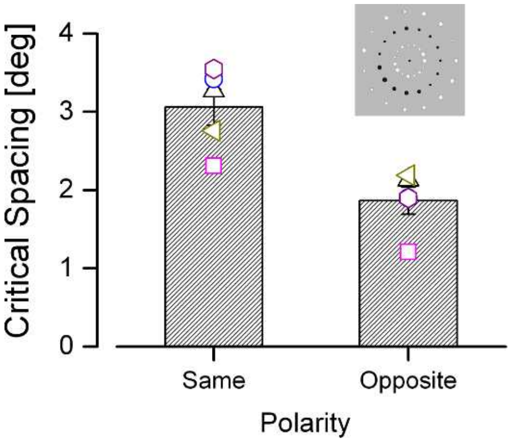

Figure 5. Critical spacing between rings of dots under two different conditions same polarity and opposite polarity, with target at 7° eccentricity. The symbols show individual results, color-coded as in Figure 2, except for two new subjects. The bars show averages with error bars ±1 *SEM*. Inset: example of stimulus with opposite-polarity target and flankers.

Crowding refers to the fact recognition of target in the periphery is difficult when surrounded by other stimuli. The critical parameter for crowding is not the distance between object contours but the distance between their centers; and this *critical spacing* is proportional to eccentricity (Bouma, 1970), approximately half the target eccentricity. This relationship is so solid, it is generally termed Bouma's law, although the precise value varies depending on stimulus characteristics and task requirements (Whitney & Levi, 2011). An important consequence of this law is that the size of the interference zone is independent of target (Bouma, 1970; Levi & Carney, 2009; Pelli & Tillman, 2008; Tripathy & Cavanagh, 2002; but see also Manassi, Sayim, & Herzog, 2012). The evidence presented here strongly supports the suggestion that motion silencing occurs only in crowded displays. Speed thresholds depended strongly on spacing of the stimulus rings. The *critical spacing* for motion silencing was about half the eccentricity of the rings, for two eccentricities (3.5° and 7°), well within the rage of parameters normally reported. Importantly, the critical spacing did not vary with a halving of object size, a signature of crowding.

It is difficult to relate the results of the first experiment, with 100 dots randomly positioned within a 5° × 8° annulus, with the second series, where the dots were uniformly positioned around three equispaced rings. The first experiment (with randomly positioned dots) yielded velocity thresholds around 0.2 rotations per second. Figure 4 suggests that with regularly spaced dots, the threshold spacing should be around 3°. The average spacing between the random dots of Experiment 1 was 1°: but as they were randomly positioned, this varied, so that 15% had spacing greater than 3°. Perhaps the discrimination (under forced choice) was achieved by this small percentage of uncrowded dots?

Crowding occurs for moving objects, with a similar dependence of eccentricity and size of critical zones as those observed for stationary objects (Bex & Dakin, 2005; Bex, Dakin, & Simmers, 2003). Crowding does not increase with speed, consistent with the fact that we find Bouma constants similar to those reported for stationary targets. Interestingly, there is also evidence that crowding occur after motion has been processed, as it is the perceived rather than actual physical position determines crowding in stimuli moving within a stationary window (Maus, Fischer, & Whitney, 2011).

In summary we believe that two mechanisms are involved in motion silencing: integration of global motion to absorb the dynamic change signals of the individual dots, and crowding mechanisms to prevent perceptual isolation of individual dots, allowing their individual changes to be monitored.

Keywords: crowding, global motion, motion silencing

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