Floating square illusion: Perceptual uncoupling of static and dynamic objects in motion

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One of the primary goals of motion analysis is to accurately track the movement of objects in the environment. We report on a novel illusion in which two objects moving with identical physical velocities have different perceived velocities, creating an apparent offset in their relative spatial positions. The stimulus is a smaller object composed of a static noise pattern superimposed on a larger object composed of dynamic noise. When the two objects are moved, the smaller object appears to lag behind the larger object. In the present study, we report our observations on this novel effect. The results of our experiments indicate that the effect arises from differences in the perceived speed of static and dynamic patterns presented in the context of moving objects.

Keywords: motion perception, object motion, spatial localization, perceptual velocity, noise patterns

Introduction

One of the most basic functions of motion processing in the biologic system is to provide an accurate estimate of the motion of objects in the world. Generally speaking, the visual system is quite adept at this task. Under some conditions, however, the visual system fails to record an accurate representation of the movement of objects and their relative spatial relations. Some relevant examples include the fluttering hearts illusion in which two color targets appear to drift apart when moved together (Helmholtz, 1867/1962), the flash lag effect where a continuously moving object is perceived as being ahead of a physically aligned stationary flashed stimulus (Krekelberg & Lappe, 2001; Nijhawan, 2002), induced motion where a stationary object appears to move as a result of the motion of another object (Dunker, 1929; Reinhardt-Rutland, 1988), and kinetic edges where motion alters the perceived position of a stationary object (Anstis, 1989). In this article, we describe a novel illusion in which two patterns spatially superimposed become perceptually uncoupled when they are moved. The stimulus is a smaller object composed of static noise (SN) centered on top of a larger object filled with dynamic noise (DN); both move together with the same direction and speed. Physically, the relative position of the two objects never changes; the smaller SN object is always centered on top of the DN object. When they move, the smaller object appears to lag behind the larger object, creating an apparent spatial offset in their relative positions (Figure 1).

We describe our phenomenological and experimental observations on this novel effect. Phenomenologically, we observed that the illusion is greatly influenced by the physical motion of the stimulus and can be seen with little or no retinal motion (i.e., while tracking the motion). We also found that the effect cannot be adequately explained by issues such as segmentation and border contrast. Experimentally, we show that the illusion is based on differences in the perceived speed of the two patterns (Experiment 1), demonstrate the role that the context of moving objects plays in creating the illusion (Experiment 2), and show that the effect does not generalize to other patterns previously reported to have different perceived speeds (e.g., equiluminance color; Experiment 3).

Phenomenological observations

In the following sections, we report on our phenomenological observations on the illusory lag in a variety of stimulus configurations. In each phenomenological test, at least five naive observers were asked to informally report on their experience of each stimulus configuration. In most cases, this entailed responding if they perceived a perceptual lag in the stimulus.

Physical motion

In our initial exploration of the stimulus, we found the illusion to be quite sensitive to the underlying motion

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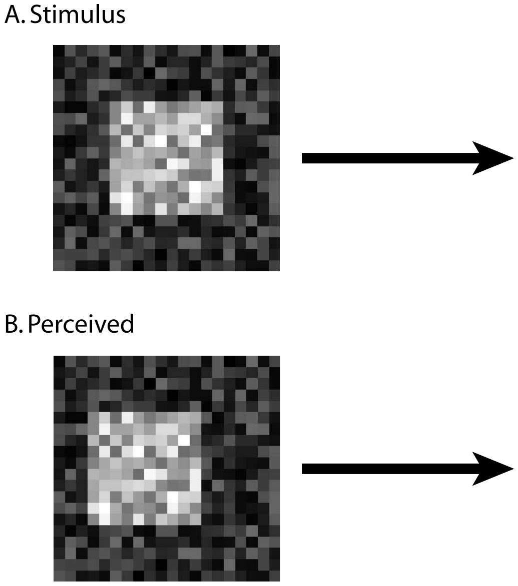

Figure 1. Stimulus. (A) A smaller SN object (highlighted for visualization purposes) is centered on a larger DN object; both objects move to the right at identical velocities. (B) Perceptually, the smaller object appears to lag, creating an illusory spatial offset.

process. The effect is most salient when the movement of the objects changes according to a random walk process (Movie 1). Most, if not all, people who view the stimulus under these conditions perceive the smaller SN object perceptually hopping around within the borders of the larger object. The effect, however, does not require the rapid direction changes and acceleration associated with a random walk. When the stimulus moves smoothly in a single direction, it becomes apparent that the smaller object is lagging behind the larger object. Sinusoidal movement of the compound object creates the percept of the smaller object smoothly sliding around within the boundaries of the larger object as if attached by a rubber band (see auxiliary MATLAB code). At a constant velocity, the effect is substantially weaker, but relatively stable spatial displacement between the two objects can be observed (i.e., a lag).

Movie 1. Random walk motion.

Retinal motion

When the motion of an object is tracked with eye movements, retinal velocity is effectively zero and, consequently, the motion of an object must be inferred based on eye position. Pursuit eye movements have been observed to have a strong influence on some motion illusions. For example, the flutter of the fluttering hearts illusion and the lag in the flash lag effect can both be abolished if observers track the motion of the object in the stimulus (Arnold & Johnston, 2003; Nijhawan, 2001). The conclusion that can be drawn from these findings is that these illusions are dependent on retinal motion. We also examined the effects of tracking the objects in our stimulus and found that the illusion remained perceptually robust. In addition, at the suggestion of one of the reviewers, we tested a condition in which observers tracked the movement of a small dot while the position of the two objects was fixed. Here, the objects move on the retina, but not physically. Under these conditions, no effect was observed. Together, these observations suggest that the illusion is based more on the interpretation of the motion of the objects rather than on the measurement of visual motion by low-level motion detectors. In addition, these observations also distinguish the reported phenomenon from the fluttering hearts illusion and the flash lag effect, both of which have some qualitative similarities.

Fluttering hearts, perceptual velocity, and border contrast

As noted previously, the illusion bears resemblance to the fluttering hearts illusion. In both cases, a pattern superimposed onto another gives rise to the appearance of relative spatial offset when the two patterns are moved. Recently, it has been proposed that the fluttering hearts illusion can be explained by differences in the perceived velocity of chromatic and achromatic borders (Nguyen-Tri & Faubert, 2003). Arnold and Johnston (2003) astutely observed that if this were the case, then one would expect the object with a lower perceptual velocity to lag progressively behind with extended viewing. When they tested this prediction, they found instead that the object appeared to jitter at a characteristic rate. They subsequently proposed a compensatory mechanism that periodically resolves spatial conflicts induced by differences in perceived velocity. Interestingly, we did not observe spatial jitter in our illusion. The smaller object appeared to move smoothly within the borders of the larger dynamic object region. Although we cannot rule out the possibility that spatial jitter was present in our illusion, as it was possible that the dynamic pattern masked the jitter, we can state that the proposed compensation mechanism appears to be insufficient to counterbalance the effect because the illusion can be observed over extended periods well beyond the characteristic rate reported by Arnold and Johnston.

Despite the aforementioned differences between the fluttering hearts illusion and the effect we observed, differences in perceived velocities of the borders of the objects remain a viable explanation for the effect. One potential source of a difference in perceived velocity is the difference in border contrast of the two objects, of which the effect of perceived speed has been well documented (Stone & Thompson, 1992; Thompson, 1982). We next examined how changing the contrast of the two critical boundaries in the illusion (SN/DN and DN/uniform gray [UG]) altered the illusion. In the original demonstration, which notably produces a strong effect, the three regions of the stimulus (SN, DN, and UG) are roughly equivalent in terms of mean luminance. This, of course, is if the spatial and temporal nonlinearities of the display and visual system are discounted. In lieu of carefully balancing the regions in terms of perceived luminance in an attempt to eliminate the effect, we chose to amplify the differences between regions to see if we could alter the perception. We first tested the illusion on a black background, effectively increasing the contrast between the dynamic region and the background. If boundary contrast were critical, then we would expect this manipulation to amplify the effect. The magnitude of the effect did not appear to be enhanced by this manipulation. The next manipulation we performed increased the border contrast between the static and dynamic regions by decreasing the mean luminance of the central static region. Here, again assuming that the border contrast is critical, the prediction would be that this would either diminish or possibly reverse the illusion. Again, the perception was not noticeably altered. In our final manipulation, we changed the mean luminance of both the static and dynamic regions. The luminance was increased in the static region and was decreased in the dynamic region. Notably, in this configuration, the motion of two objects could be accurately tracked based entirely on luminance or first-order properties. Interestingly, the effect was still not noticeably altered. Together, these observations indicate that luminance border contrast is not critical for the illusion.

Segmentation

The two objects physically move together, but, clearly, the visual system interprets them as individual entities, at least to the extent that they are assigned unique motion estimates. This suggests that the objects are segmented and that their speeds are estimated separately. Given that the objects are treated as separate, could it then be that the segmentation of the smaller object is in some way hindered by the presence of the dynamic background? If so, this may result in a temporal delay in the processing of the motion of the smaller object and may offer a potential explanation for the illusion. Our observations indicate that this is not the case. Adding cues to facilitate the segmentation of the smaller object, such as making the objects different in color or mean luminance (see above), fails to diminish the effect. In addition, we tested a condition in which the two objects were not in physical contact with one another. The dynamic region was changed to a frame surrounding the smaller static pattern, creating a gap between the two objects' boundaries. The lag was still found to be present after this manipulation, indicating that the effect cannot be explained by difficulties in the segmentation of the smaller object. Furthermore, this observation can also rule out any explanation based on direct interactions between the boundaries of the two objects.

Experimental observations

In the following sections, we tested various hypotheses about the cause of the lag effect. Experiment 1 examined the nature of the perceptual lag by testing various alternatives that could account for the lag in the illusion. Experiment 2 examined if the perceived velocity of the component patterns could explain the effect and the role of context in creating the illusion. In Experiment 3, we measured the effect as a function of velocity and tested to see if the effect would generalize to other moving stimuli known to have different perceived velocities (e.g., equiluminance color boundaries).

Experiment 1: Temporal latency or velocity effect?

The perceptual consequence of the illusion is an offset in the relative spatial positions of the two objects. The illusory offset between the objects could potentially arise from a spatial and/or a temporal misperception of the motion of the two objects. Figure 2A shows predictions for three alternative explanations for the lag for a repeating triangle motion trajectory. The first alternative of a pure spatial offset can quickly be dismissed as it would predict that the smaller object would lead the larger object after the stimulus changed directions. The remaining alternatives are as follows: (1) there is a difference in the temporal latency in the perception of the motion of the two objects and (2) the two objects have different perceptual velocities. To test these alternatives, we had

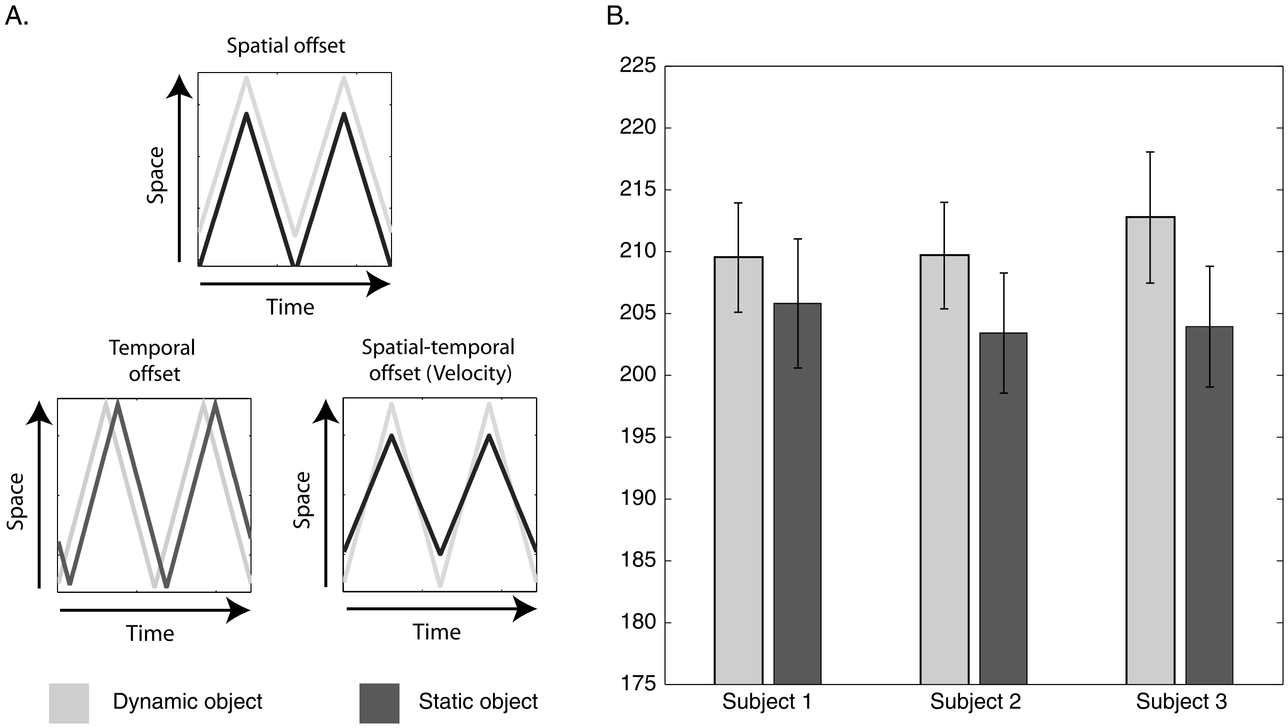

Figure 2. Reaction time experiment. (A) Space–time plots of predictions for three explanations for the perceptual lag. Spatial offset: A lag generated by a difference in the perceived spatial position of the two objects. Temporal offset: A lag created by a temporal delay in processing the motion of the static object. Spatial–temporal offset: A lag attributed to differences in perceived velocity of the two objects. (B) Results for the reaction time experiment. Vertical bars are the standard error of the means (±1 *SE*).

subjects perform a simple reaction time experiment while the stimulus moved in a triangle motion trajectory. Subjects were instructed to make a judgment about the time when either the static or the dynamic object changed directions. The predictions for the two alternatives are clear. If the effect is based on a temporal offset, then subjects will judge the change in the direction for the dynamic object to occur before the static object. If the effect is based on differences in the perceived velocity, then subjects will judge the change in direction to occur at the same time for both objects.

Methods

Participants

Two naive observers and one of the authors (TC) participated in the experiments. All were experienced psychophysical observers and had normal or corrected-to-normal vision.

Visual display apparatus

Subjects were tested in a dimly lit room at a viewing distance of 57 cm. Stimuli were displayed on a 19-in. Mitsubishi Diamond Pro monitor (1024 × 768 at 100 Hz) controlled by a Macintosh G4 computer with a linearized gray scale luminance output ranging from 10 to 100 cd/m^2. Stimuli were generated in MATLAB utilizing functions provided by the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997).

Reaction times

A separate Macintosh PowerPC 8600 computer recorded each subject's reaction times. The visual display and reaction time computer were synchronized through the serial port.

Stimuli

The stimulus was the same configuration as in the original demonstration. A uniformly distributed random noise pattern (2 × 2 deg in visual angle) with a mean luminance of 55 cd/m^2 was centered on top of a larger DN pattern (3 × 3 deg of visual angle). Dynamic regions were created by generating a new noise pattern (55 cd/m^2) at each refresh of the monitor. The stimulus moved horizontally at a speed of 4 deg/s; at a randomly determined point, it switched directions and continued at the same velocity for 2 s.

Procedure

Subjects fixated and were instructed to respond as quickly and as accurately as possible to the reversal of the motion. For each trial, the point at which the motion reversed directions was randomly determined, but constrained to be within ±5 deg of the fixation point. In separate runs, subjects were asked to make their judgments based on either the static or the dynamic region of the stimulus. Data were collected in three 50 trial blocks per subject for each of the conditions (150 trials per condition). Data were pooled across runs for each subject. Responses were removed from the analysis if they were either prior to the change in direction or longer than 1 s, resulting in approximately 4% of the data being rejected. Data are reported as the mean reaction time for the two conditions tested. The standard error of the means is shown as vertical bars (±1 *SE*).

Results

The results of the experiment are shown in Figure 2. No significant difference was observed in the reaction times for detecting the change in direction of the two patterns. There was a small trend (5–9 ms) present in the data indicating that subjects were slower to react to the dynamic pattern. With additional trials, it is possible that this small difference would have reached significance. This result, however, even if significant, would predict that the static pattern would lead (the opposite of the effect observed in the illusion). We therefore take the results of the experiment as evidence supporting the conclusion that the lag is a consequence of differences in the perceived velocity of the two objects.

Experiment 2: Perceived velocity of component patterns

The results of the reaction time experiment indicated that the illusion is better explained by differences in the perceived velocity of the component patterns. A variety of factors could potentially be influencing the perceived velocity of the two objects in the stimulus. These factors include the contrast (Stone & Thompson 1992; Thompson 1982), the features that define the motion (e.g., first- and second-order properties; Gegenfurtner & Hawken, 1996; Ledgeway & Smith, 1995), the size and background (Blakemore & Snowden, 2000; Brown, 1931; Gogel & McNulty, 1983; McKee & Smallman, 1998), and the method the visual system uses to track the motion (i.e., attentional tracking; Cavanagh, 1992). In the next set of experiments, we measured the perceived velocity of the component patterns of the stimulus to test whether systematic biases in the velocities of the two patterns explain the effect. Perceptual velocity was measured using a two-alternative forced-choice (2AFC) procedure that adaptively changed the velocity of the test patterns to match the speed of a standard target. The perceived velocity of the patterns was measured in two ways. In the first experiment, square wave gratings were constructed based on the constituent patterns of the stimulus (see Figure 3A). This dissociated the measurement from the potential influence of the perception of moving objects. In the second experiment, the perceived velocity of the patterns was measured with small targets that can be considered as objects embedded in various backgrounds, thus providing an opportunity to contrast them with the first set of experiments revealing the contribution of context to velocity judgments.

Experiment 2A: Grating motion

In the first experiment, the object context was removed and the perceived velocity of the component patterns was measured using grating stimuli. Stimuli were square wave gratings constructed of the constituent patterns in the illusion: static random noise (center region), dynamic random noise (surrounding region), and UG (background). The first two conditions were intended to represent the edge boundaries present in the stimulus, SN with DN (SN–DN) and DN with UG (DN–UG). The third condition, SN with UG (SN–UG), was measured to evaluate the possible influence of the dynamic pattern on the perceived velocity of the SN pattern. Graphical depictions of the three experimental stimuli and the standard target used for comparison are shown in Figure 3A.

Methods

Stimuli

Stimuli were vertically oriented 1 cycle/deg of square wave gratings that drifted either to the left or to the right. The three experimental stimuli used in the experiments were SN–DN, DN–UG, and SN–UG gratings (shown in Figure 3A). SN patterns were uniformly distributed random noise with a mean luminance of 55 cd/m^2. DN patterns were identical to SN patterns except for the fact that a new noise pattern was generated at each refresh of the monitor. UG patterns had a luminance of 55 cd/m^2. All the experimental stimuli were compared with a standard target, a luminance-defined square wave grating with alternating bands 45 and 75 cd/m^2 in luminance.

Procedure

Subjects were instructed to fixate throughout the experiment. On each trial, each subject's task was to judge which of the two simultaneously presented gratings moved faster. Stimuli were presented in two windows 4 × 4 deg of visual angle. The inner edges of the two windows were 0.5 deg to the left and the right of a central fixation point. The standard target and test pattern were randomly assigned to the left and right windows on each trial. The standard target always

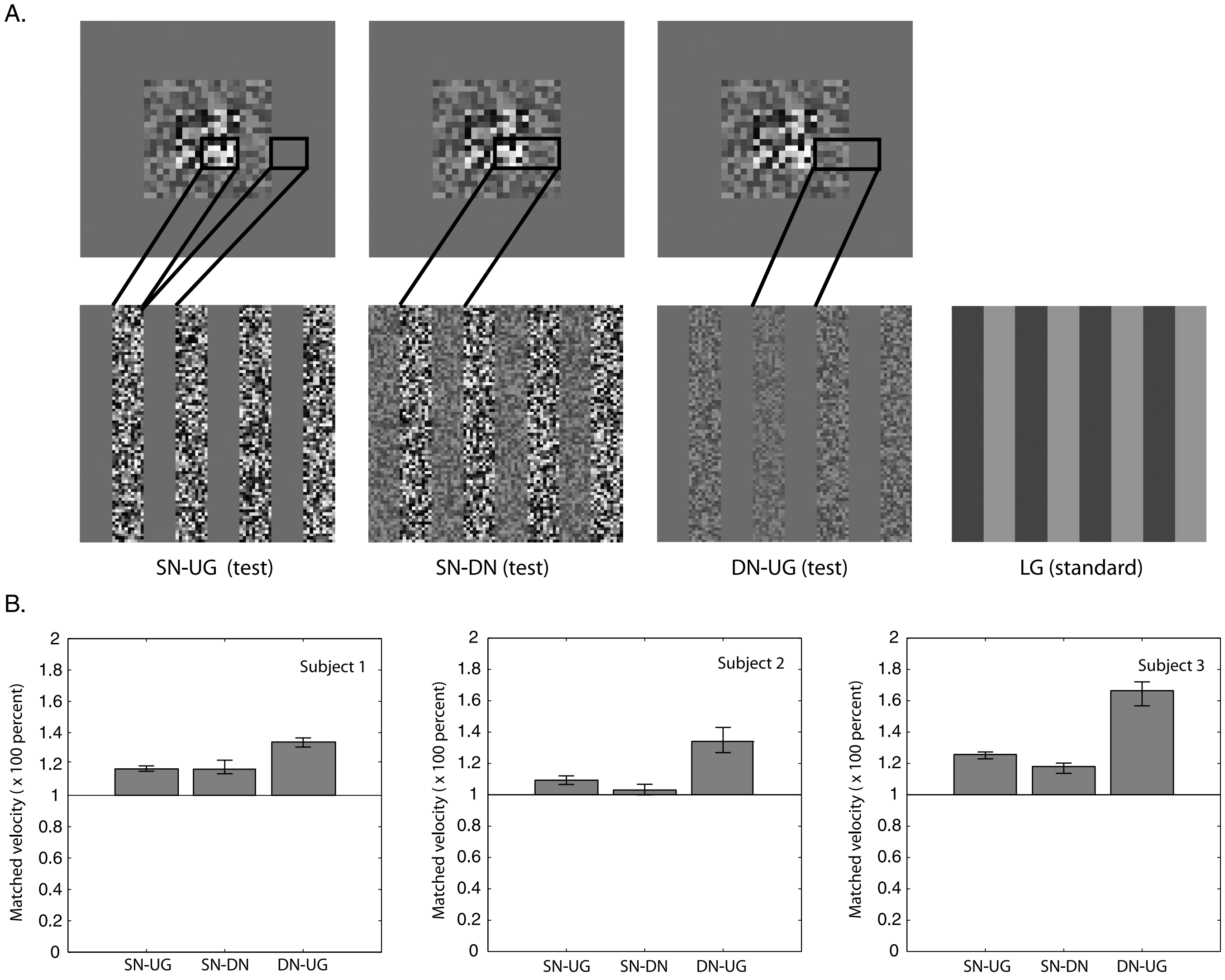

Figure 3. Gratings experiment. (A) Graphical depictions of the stimuli used in the experiments (dynamic patterns shown in reduced contrast). (B) Results for three subjects. Velocity matches were taken as the 50% point of fitted psychometric functions. The results of the experiment are plotted as the percentage increase or decrease in velocity to match the velocity of the standard target. Note that increases in matched velocity imply that the stimulus appeared slower than the standard target. Vertical bars are 95% bootstrapped confidence intervals.

moved at a fixed velocity of 4 deg/s. The velocity of the test grating was determined by an adaptive staircase procedure. In an effort to minimize eye movements, motion in the two windows was always in the opposite direction. The direction of motion in the two windows alternated between trials to avoid motion adaptation.

Data were collected using a 2AFC procedure. QUEST, an adaptive procedure, was used to track the 25%, 50%, and 75% points on the psychometric curve (Watson & Pelli, 1983). Stimuli were presented for 1 s, followed by a 0.5-s delay after a subject responded. Three 50 trial blocks were run for each of the three points on the psychometric curve for each test pattern (450 trials per condition). Data were pooled across blocks for each experimental condition. Psychometric curves were fit with a cumulative Gaussian function, and bootstrapped confidence intervals were computed using the psignifit toolbox for MATLAB (Wichmann & Hill, 2001a, 2001b). The fit of the psychometric curve was verified using a χ^2 test on higher order polynomial models, which did not yield any significant improvement on the fit. Velocity matches, taken as the 50% point from fitted psychometric functions, are plotted as the percentage increase or decrease in velocity relative to the luminance standard target. This point, along with a 95% bootstrapped confidence interval, is shown in the plots for each of the conditions for each subject (Figure 3B).

Results

Results of the experiment are shown in Figure 3. In the plots, a value of 1 indicates that the test and standard target were matched at identical speeds. Values below 1 indicate that the speed of the test pattern needed to be decreased to match the speed of the standard target; values above 1 indicate that the speed of the test pattern needed to be increased.

In all three subjects, the speed of the test patterns needed to be increased to match the velocity of the luminance grating, indicating that the patterns were perceived as moving slower than the standard luminance grating. There was a significant effect in two of the three subjects (Subjects 2 and 3) for the SN–UG gratings versus the SN–DN gratings, indicating that the SN–DN gratings are perceived as moving faster. The largest effect, and perhaps the one most relevant, was between the DN–UG gratings and the two test patterns containing SN patterns (SN–DN and SN–UG). This effect was significant in all three subjects, indicating that the dynamic patterns are perceived as moving slower than the other two stimuli. If the results of the experiment were evaluated in terms of the stimuli's first- and second-order properties, then the results would be consistent with the finding that second-order stimuli appear to move slower than first-order stimuli under similar conditions (Gegenfurtner & Hawken, 1996). The effect, however, is in the opposite direction of the lag illusion we observed and report in this article.

Experiment 2B: Object motion

The results of the grating experiment were inconsistent with the observed properties of the illusion. Grating stimuli are both periodic and windowed and thus do not reflect the properties of the illusion in its original configuration. The second experiment measured the perceived velocity of the component patterns within the context of moving objects. In the previous experiment, the test patterns were constructed to reflect the edge boundaries of the illusion. The design of the stimuli in the present experiment was intended to simulate the motion of the objects on their respective backgrounds. To highlight this figure ground relation, we abbreviated the conditions with "/" instead of "–." The first two conditions tested adhere to the object background relation present in the illusion, an SN object on a dynamic background (SN/DN) and a DN object on a gray background (DN/UG). Again, we tested an SN pattern with a UG background (SN/UG) to monitor the influence of the DN pattern on the perceived velocity of the static pattern. All the stimuli again were compared with a standard luminance-defined object (LO in figure). Graphical depictions of the three test stimuli and the standard target are shown in Figure 4A.

Methods

Stimuli

Stimuli were square objects 2.5 × 2.5 deg of visual angle moving horizontally either to the left or to the right presented on background patterns that were 3.5 deg in height and extended the width of the monitor (~36 deg). The three experimental stimuli tested were SN/DN, DN/UG, and SN/UG. The static, dynamic, and UG patterns were generated in a fashion identical to that in the previous experiment. The standard stimulus was a luminance-defined square 45 cd/m^2 moving on a 75-cd/m^2 background.

Procedure

Subjects were instructed to maintain fixation throughout the experiment. Their task was to judge which of the two simultaneously presented square objects moved faster. Stimuli were presented in windows that were 3.5 deg in height and 36 deg in width, the same as the size of the background pattern. The edges of the windows were 0.5 deg above and below fixation. The standard and comparison targets were randomly assigned to one of the two windows on each trial. Stimuli alternated moving left to right and right to left between trials. Stimuli were presented for 1 s, followed by a 0.5-s delay after a subject responded. The standard target moved at a fixed velocity of 4 deg/s. Identical to the previous experiment, an adaptive staircase procedure was used to determine the velocity of the target. The fitting of the psychometric curves was also the same as in the previous experiment. Fits were verified using a χ^2 test on higher order polynomial models that did not yield any significant improvement (Wichmann & Hill, 2001a, 2001b). Velocity matches were again taken as the 50% point from fitted psychometric functions and are plotted as the percentage increase or decrease in velocity relative to the luminance standard target.

Results

The results of the experiment are shown in Figure 4B–D. Two of the three subjects showed a significant effect of SN/UG in reference to SN/DN, indicating that the perceptual velocity of the SN objects is in some way reduced by the presence of the dynamic background. This result is consistent with the notion that noise from the dynamic pattern is integrated into the velocity estimate of the static pattern, producing a decrease in the perceptual velocity (Zanker & Braddick, 1999), and would be consistent with the observed properties of the illusion. The largest effect for all three subjects was for the condition in which the dynamic pattern was brought to object status. This effect was significant for contrasting both the DN/UG versus the SN/DN and SN/UG. Notably, the direction of the effect has changed from the results of the grating experiment. The dynamic patterns, when placed in the context of a moving object, now are perceived as moving faster than the two conditions in which the static pattern was displayed as a moving object.

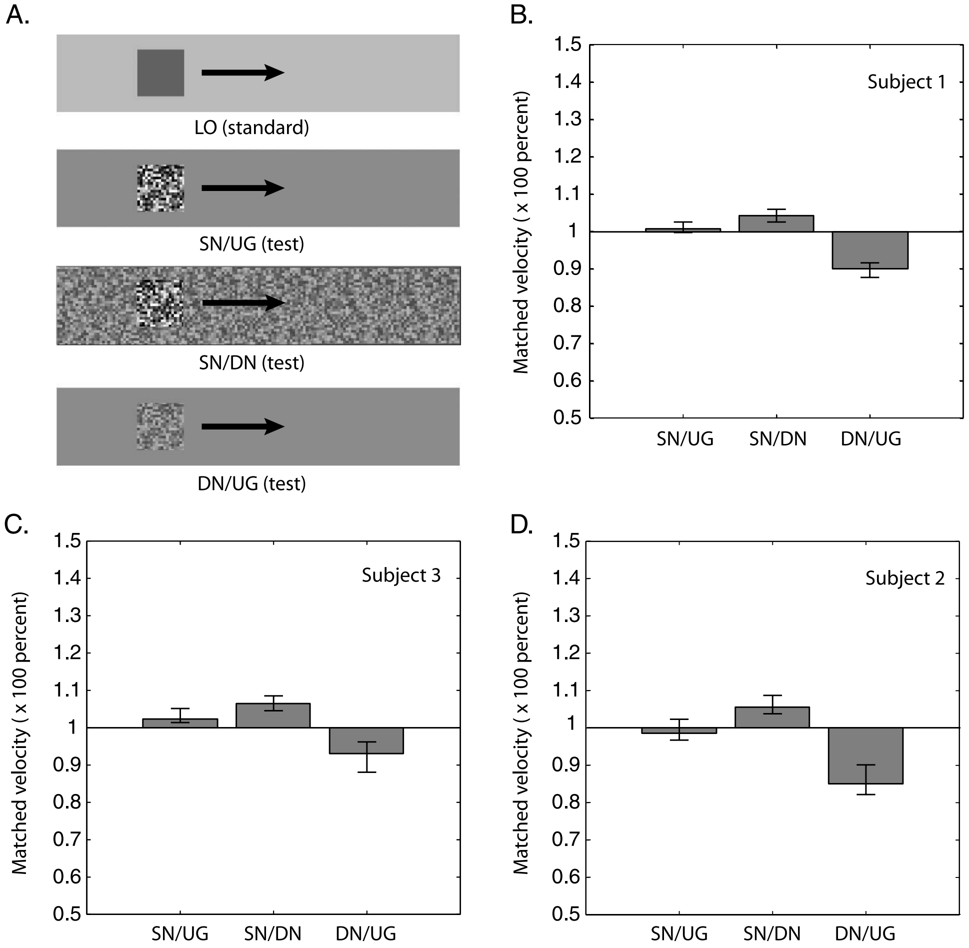

Figure 4. Object motion experiment. (A) Graphical depictions of the stimuli used in the experiments (dynamic patterns shown in reduced contrast). (B–D) Results for three subjects. Velocity matches were taken as the 50% point of fitted psychometric functions. The results of the experiment are plotted as the percentage increase or decrease in velocity relative to the luminance standard target stimulus. Vertical bars are 95% bootstrapped confidence intervals.

SN patterns are perceived as moving slower on dynamic backgrounds than on UG backgrounds, and objects composed of DN appear to move faster than objects composed of SN. These findings provide a basis for an explanation for the lag effect presented in this article. Of the two factors, the latter appears to have more weight in generating this phenomenon. We favor this view for two reasons. First, the effect size for the dynamic pattern was larger than that for the static patterns in all three subjects. Second, we observed earlier that the two patterns did not have to be in contact with one another to observe the effect. This manipulation presumably would diminish the noise integrated into the static pattern velocity estimate. Still, the results of the experiment show that the presence of DN pattern does influence the perceived velocity of the static pattern and may be a contributing factor.

The most interesting finding drawn from these experiments was the effect of context on the stimuli. Dynamic patterns appear to move slower than static patterns with grating stimuli but faster when presented in the context of moving objects. This observation is intriguing because the stimuli in the two experiments were very similar. Both experiments used the same component patterns (SN and DN) moving at identical velocities (4 deg/s). Because the patterns were the same in both experiments, it would be difficult to account for such a discrepancy in results based on image properties such as contrast, spatial frequency, or transients in the stimulus (Stone & Thompson, 1992; Thompson, 1982; Treue, Snowden, & Andersen, 1993). So, why did we get such a radically different result for the two experiments? One can only speculate, but one possibility is that the visual system used different mechanisms for estimating the motion in the two conditions. For grating patterns, the visual system may have relied more heavily on early motion detectors that are more susceptible to noise to generate velocity estimates. The perception of the speed for moving objects, in contrast, may have relied on alternative methods for estimating velocity (e.g., attention tracking). In this case, the additional motion energy from the DN pattern may be erroneously attributed to the velocity estimate of the motion of the object.

Experiment 3: The effect of velocity and generalizability

We next measured the effect of increasing velocity on the magnitude of the lag in the illusion. To quantify the effect, we had the subjects freely view the stimuli and perform a perceptual nulling task. Subjects were instructed to adjust the speed of the smaller object to match that of the larger object such that the two objects had no relative motion. In addition to a condition that mimicked the configuration of the illusion (DN), we also had the subjects perform the task with other patterns for comparison purposes. The additional conditions were equiluminant color (EQ) boundaries, low-contrast (LC) boundaries, and high-contrast (HC) boundaries. Notably, each of these conditions previously has been reported to alter perceptual velocity (Cavanagh, Tyler, & Favreau, 1984; Stone & Thompson, 1992; Thompson, 1982).

Methods

Stimuli

A square object 2 × 2 deg of visual angle was superimposed onto the larger object 4 × 4 deg of visual angle (Figure 5A, top). Both objects moved horizontally in oscillating sinusoidal motion trajectory. Velocity was manipulated by changing the temporal frequency of the stimulus (Figure 5A, bottom). Velocity estimates shown at the bottom of the figure were approximated using the slope of the sinusoid for the middle 80% of the curve between the negative and positive peak. The three velocities tested were 12, 20, and 28 deg/s. The velocity of the larger object was fixed to one of the corresponding velocities. The velocity of the smaller object was under the control of the subject. On each trial, the initial velocity of the smaller object was randomly set to be ±20% of the fixed velocity of the larger object.

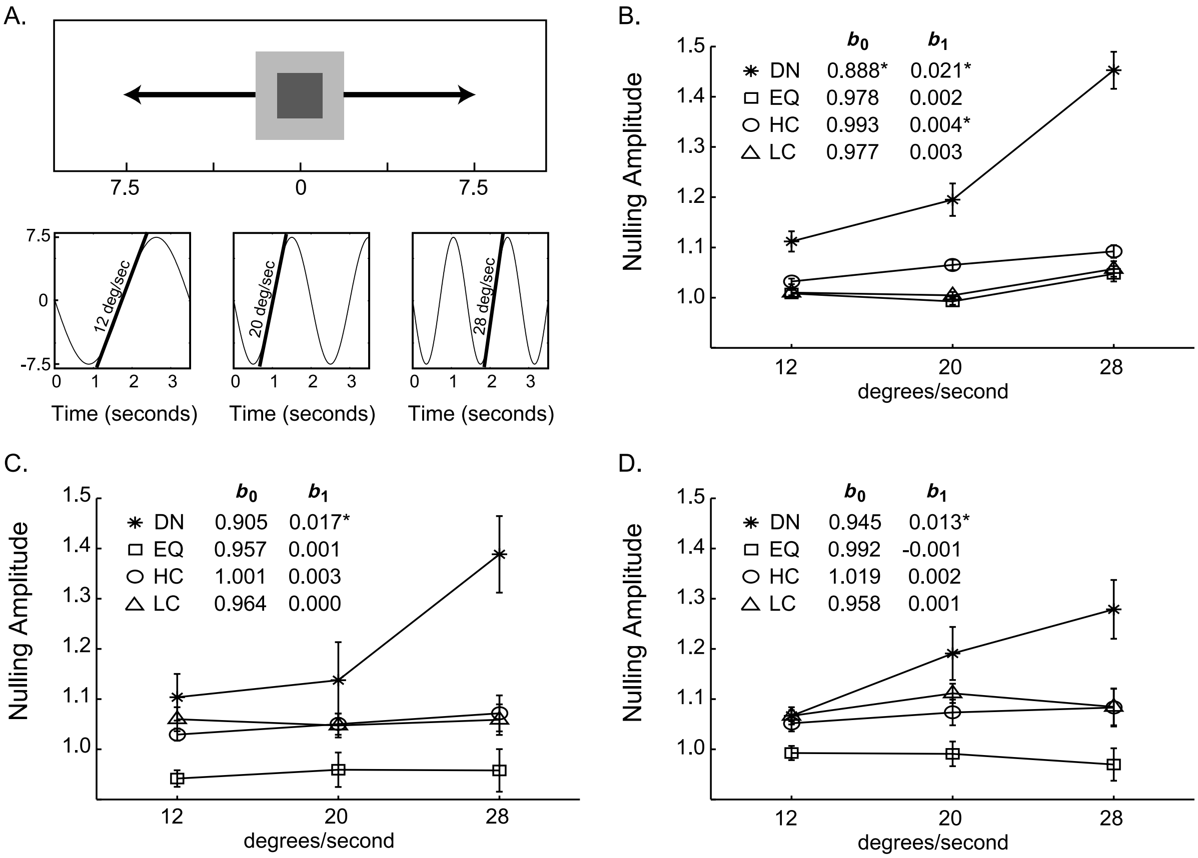

Figure 5. (A) Graphical depiction of the stimulus configuration and space–time plots of the sinusoidal motion profile used for the three speeds tested: 12, 20, and 28 deg/s. (B–D) Results of the experiment are plotted as the nulling amplitude of the smaller object. The four experimental conditions were DN, EQ, HC, and LC. Vertical bars are the standard error of the means (±1 *SE*). Insets show the results of regression analyses (b_0 = intercept; b_1 = slope). Values marked with (*) indicate a significance level greater than .01.

The four stimuli tested were dynamic noise boundaries, equiluminance color boundaries, low luminance contrast boundaries, and high luminance contrast boundaries. The smaller object was an SN pattern for all the conditions. The boundary between the larger object and the background in stimulus was determined by the experimental condition:

1. DN–dynamic patterns were generated identically to the previous experiment and set on a UG background (55 cd/m^2).
2. EQ–the larger object was shown in green and the background was in red. Prior to the experiment, the equiluminance point was determined experimentally for each subject using a minimal speed criterion (Cavanagh et al., 1984).
3. LC–the larger object was 52 cd/m^2 and the background was 58 cd/m^2.
4. HC–the larger object was 80 cd/m^2 and the background was 30 cd/m^2.

Procedure

Subjects freely viewed the stimulus at a fixed distance of 57 cm. The subjects' task was to adjust the speed of the smaller object so that the two objects had no relative motion. In terms of the stimulus, the subjects' adjustments corresponded to an increase or decrease in the amplitude of the sinusoid for the motion of the smaller object. Subjects were given an unlimited amount of time to make their settings. Subjects made nine settings for the three velocities tested (12, 20, and 28 deg/s) for each condition. All trials were randomly intermixed. Results of the experiment are plotted as the mean amplitude settings made by a subject as a function of the fixed velocity of the larger object (Figure 5B–D). The standard error of the means is shown as vertical bars (± 1 *SE*). Regression analyses were performed on raw amplitude settings.

Results

The results of the experiment are shown in Figure 5. The plots show the mean amplitude setting made by a subject as a function of the fixed speed of the larger object (12, 20, and 28 deg/s). For example, Subject 1 (viewing the dynamic pattern at the slowest speed of 12 deg/s) increased the amplitude of the motion of the smaller object by roughly 11%. The results of regression analysis are shown in the insets. The estimate of the intercept for all the conditions was not significantly different from 1 with one exception (Subject 1 in the DN condition). This result is reassuring in the sense that if the data were to be extrapolated to 0 velocity, then the motion of the two objects would be identical. In all three subjects, the DN condition shows a steady increase in the nulling amplitude for increasing speeds. The regression confirmed that this effect was significant ($p < .01$) for all subjects. In contrast, the slope estimate for the three other conditions (EQ, HC, and LC) was not significantly different from 0 with one exception (Subject 1, HC). Taken together with a nonsignificant effect for the intercept, this indicates that subjects were able to accurately match the motion of the two objects for these conditions.

With the exception of the condition with the dynamic pattern (EQ, HC, and LC), subjects were able to closely match the motion of the smaller object to that of the larger object. For the dynamic stimulus, subjects clearly perceived a lag, and the magnitude of this effect grew as a function of velocity. Data from two of the three subjects (Subjects 1 and 2) hinted that this function may be nonlinear in terms of the raw amplitude settings. If the data were to be considered strictly in terms of velocity, as opposed to raw amplitude, then the function would be nonlinear for all the subjects. For example, Subject 1 increased the amplitude by 11% at the slowest speed. This would correspond to roughly an increase of 1.3 deg/s over the base velocity of 12 deg/s. At the highest velocity tested, the same subject required a 45% increase to null the effect. Thus, we can conclude that our effect grows nonlinearly as a function of velocity and does not generalize well to other patterns observed to alter perceptual velocity.

The results of the experiment can also speak of the relationship between the illusion and two related phenomena. The first is the phenomenon of induced motion. Briefly, induced motion is when a stationary stimulus appears to move as a result of adjacent motion (Reinhardt-Rutland, 1988). This is typically done with a dot (induced stimulus) and frame (inducing stimulus) configuration. When the frame moves, the dot appears to move in the opposite direction. The reader may note that this configuration is similar to that of the illusion presented. If the dynamic region of the stimulus is viewed as the frame and the static region as the dot, then the lag in the stimulus could potentially be explained by induced movement. The challenge for this proposition would be that, physically, the two objects have no relative motion, as in the case of induced motion. This proposition could be revitalized by considering differences in perceptual velocity as a source of relative movement. The data from the present experiment can in part rule out this as an explanation for our effect. Three conditions that presumably would alter the perceived speed of the larger object were tested. In each of these conditions, subjects were able to accurately match the motion of the two objects. Thus, perceptual velocity can be considered, at best, a weak source for generating induced movement. Consequently, an explanation based on induced movement appears to be inadequate to explain the effect.

A second related phenomenon is that of temporal capture (Treue et al., 1993), where the apparent speed of moving dot patterns increased if temporal noise was introduced into the stimulus. Although temporal capture and the illusion we presented here are likely to be related, they behave differently with respect to increasing velocity. Treue et al.'s (1993) observations on the temporal capture indicated that the effect was strongest at low velocities (4 or 6 deg/s) and diminished at higher velocities (12 deg/s). We observed the opposite effect. The effect was smallest for the lowest velocity tested (12 deg/s) and increased as a function of increasing velocity.

Finally, it is noteworthy that subjects freely viewed the stimulus while making their settings. Subjectively, participants indicated that the strategy they employed during the task was to use eye movements to track the movement of the stimulus. Because the effect could be measured under these conditions, these results confirm our previous observation that the effect is present during pursuit eye movements.

Summary/conclusions

We have introduced an illusion based on the relative motion of two objects. The illusion arises from two superimposed moving objects, one composed of static noise and the other composed of dynamic noise, that when moved appear to become perceptually uncoupled from one another. In the present study, we studied several aspects of the stimulus in an attempt to generate an explanation for this novel effect.

We first examined how the motion of the stimulus, both physical and retinal, altered the percept. We found that changing the physical motion of the stimulus greatly influenced the percept. The illusion ranged from the striking appearance of the two objects being completely unhinged from one another during a random walk process to barely noticeable at slow constant velocities. Experiment 3 explored the effect of velocity further by manipulating the velocity of the stimulus. Using a perceptual nulling procedure, we found that the magnitude of the effect increases nonlinearly as a function of velocity. We also examined if retinal motion was required to generate the illusion, as this manipulation has previously been reported to diminish the flash lag effect and the fluttering hearts illusion (Arnold & Johnston, 2003; Nijhawan, 2001), two phenomena that have some qualitative similarities to the present effect. Unlike the flash lag effect and the fluttering hearts illusion, retinal motion was not necessary to create the illusion. When subjects were instructed to track the motion of the stimulus, the percept was not noticeably altered. This observation was confirmed in Experiment 3, where we found a measurable effect while subjects tracked the motion of the stimulus. The implication of this observation is that illusion is more likely to be based on the high-level interpretation of the motion of the objects as opposed to the measurements of the visual motion read out by low-level motion detectors because tracking the motion of an object effectively eliminates retinal motion.

We also investigated what features or attributes of the stimuli were critical for creating the illusion. Our intuition, which turned out to be correct, was that it was the dynamic pattern in the stimuli. Although dynamic patterns can be classified as second-order motion stimuli, our informal observations indicated that the effect did not generalize well to other second-order patterns. In Experiment 2, we tested if a similar effect could be generated by using other patterns known to alter perceptual velocity (i.e., luminance contrast and equiluminance). The results of the experiment indicated that a subject could successfully match the motion of objects for low and high luminance contrast boundaries and for equiluminant boundaries color. This was not the case for the static and dynamic patterns, indicating that these patterns are a critical feature of the illusion.

The illusion manifests as a shift in the apparent spatial position of the two objects relative to one another. The spatial offset between the two objects could potentially arise from a number of sources. In Experiment 1, we tested if the spatial offset could best be attributed to a temporal offset or a difference in the perceived velocity of the two objects. The results of the experiment indicated that the spatial offset is best explained by differences in the perceived velocity of the two objects. In Experiment 3, we measured the perceived velocity of the component patterns of the stimulus. The results of the experiment indicated that the lag could be explained by differences in the perceived velocity of the static and dynamic patterns. Interestingly, this effect was only present when the patterns were tested in the context of moving objects.

The most interesting observation made in our exploration of the illusion was the perceived velocity of moving pattern could be altered by changing the context in which motion information is presented. The effect of context has been examined previously for contrast, which, as noted earlier, has been reported to alter perceptual velocity (Blakemore & Snowden, 1999). The authors found that the effect of contrast on perceptual velocity generalized well to a variety of moving patterns including two conditions that resemble the conditions tested here (see Experiment 1). Our experiments indicated that this was not the case for the static and dynamic patterns of the illusion. Dynamic patterns appeared to move slower than static patterns for grating stimuli but faster in the context of moving objects. Our speculative answer to account for these results is that the visual system may be utilizing strategies for estimating the motion of grating patterns and patterns presented in the context of moving objects. This meshes well with the long-held distinction between low-level and high-level systems of motion analysis (Braddick, 1980; Cavanagh, 1991; Julesz, 1971). In each of these models, the low-level motion system measures motion by reading out the activity of motion detectors like those found in the primary visual cortex (Hubel & Wiesel, 1968). Two of our observations indicate that the illusion is not based on low-level motion analysis. First, the effect was perceptually robust in the absence of retinal motion. Second, context appears to play an important role in the perceived velocity of the patterns when other low-level factors can be accounted for (e.g., contrast, spatial, and temporal frequency). This leads us to the obligatory conclusion that the illusion is a high-level phenomenon.

A speculative explanation for the illusion can be generated by making two assumptions. The first is that when the visual system successfully segments an object in the scene, it can alternatively switch to a high-level mechanism for velocity estimation. Previously, it has been reported that this high-level mechanism can support more accurate velocity estimates (Cavanagh, 1992); thus, it would be advantageous for velocity estimation. This assumption is in place to explain why context is necessary to generate the effect. The second assumption is that this high-level motion mechanism integrates spatial–temporal noise in a manner that can produce a net gain in the velocity estimate. This, for example, could occur if greater weight is given to local velocity estimates that coincide with the direction of motion of a moving pattern. This explanation, however, remains well within the realm of speculation.

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