Cortical distance determines the perception of two competing types of visual motion

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MOTION REVERAL
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Abstract

We did stuff.

1 Introduction

2 General Methods

2.1 Observers

Observers were one of the authors (P.B.M.) and SOME NUMBER OF naïve observers (). All had normal or corrected-to-normal vision.

2.2 Equipment

Stimuli were presented on a flat CRT video monitor (ViewSonic PF790). Its resolution was set to 800×600 pixels over a display area of 35.5×35.5cm and it used a 120Hz refresh rate. Experiments were programmed in MATLAB using the Psychtoolbox (**?**) and Eyelink toolbox extensions (**?**), along with custom OpenGL code. Grayscale stimuli were shown using equal red, green, and blue signals. The monitor was calibrated using a Tektronix photometer. A 50% gray background was chosen to lie at the midpoint between mimimum (0.1286cd/m^2) and maximum (60.97cd/m^2) luminances, which were in turn measured as patches against the gray background. A hardware lookup table with 10-bit resolution was constructed to linearize the display luminance.

Subjects sat behind a blackout curtain so that ambient illumination was mostly due to the monitor and viewed the screen binocularly using a chin and forehead rest with the eyes 60cm from the screen. Eye position was monitored using a video-based eye tracker (EyeLink 1000; SR Research) using a sample rate of 1000Hz. Eye movements were recorded but are not reported in this paper. Subjects gave responses by turning a knob (PowerMate; Griffin Technologies) with their preferred hand.

2.3 Stimuli

Example stimuli are shown in **??**. The stimuli consisted of a number of identical elements arranged into a circle, each with a direction of motion. A space-time diagram of the motion of a single elment is shown in **??** (x being taken along the circle that the element travels on.) The motion of each elament consisted of a set of 5 discrete appearances of an envelope, each offset by regular space (Δx) and time (Δt) intervals. Within each envelope, the carrier was continuously in motion with a constant temporal frequency ω. The temporal profile of each envelope was Gaussian, with standard deviation $d/2$; at the peak of the temporal envelope the carrier was in cosine phase. At right angles to the direction of motion, the envelope is Gaussian envelope with standard deviation $w/2$. Along the direction of motion, the carrier modulated by the spatial envelope forms a Cauchy filter function (**?**) with peak spatial frequency f. The equation describing the luminance profile of a patch as a function of position and time is then:

$$L(x,y,t) = \cos^n(\tan^{-1}(fx/n))\cos(n \cdot \tan^{-1}(fx/n) + \omega t)e^{-(t/2d)^2-(y/2d)^2}$$

with the direction of motion along x. The spatial bandwidth parameter n was set to 4 for all stimuli.

The examples in **??** have the following settings, the same as used in **??**: For all trials, $\Delta t = 100$ms, $\omega = 10$Hz, and $d = 0.067$s. For stimuli at 10° eccentricity, $f = 1.33$cyc/°, $\Delta x = 0.75°$, and $w = 0.75°$, and these three parameters were scaled proportionately to eccentricity.

We used three types of motion stimuli, illustrated as (x,t) diagrams in **??** and demonstrated in **??**. In *congruent* stimuli the displacement of each successive presentation of a motion element (Δx) agreed in direction with the short-range motion contained in each element. In *incongruent* stimuli, the direction of displacement was opposite the direction of short-range motion. In *counterphase* stimuli, the motion elements contained a counterphase flicker formed by superposing motion elements with equal and opposite short-range motion content. That is, the counterphase stimuli have the same spatial and temporal frequency distribution as in congruent and incongruent stimuli, but their motion energy is equivocal between opposite directions. The second stimulus in **??** shows counterphase local motion. The contrast of the local motion elements was 70.7% for congruent and incongruent trials, and 100% for trials using counterphase stimuli (that is, 50% contrast in each direction). These contrast values appeared to equalize the subjective contrast of the stimuli of each type.

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(a) Example stimuli in space-time form, where time progresses down along the vertical axis. All plots depict a stimulus containing a single element whose carrier motion is to the right. Stimuli were *congruent*, *conterphase* or *incongruent*, based on whether the direction of carrier agreed with that of long-range motion. Counterphase stimuli are a superposition of congruent and incongruent stimuli.

(b) A demonstration of the three stimulus types, at low density. In all cases the envelope motion is counterclockwise, while the carrier motion varies.

Figure 1: Stimuli used in this report.

3 Demonstrations and Subjective Observations

It is worth commenting about some properties of this type of stimulus that can be subjectively observed, and (so far as we can tell) aknowledged by almost all colleagues we show our displays to, even though we do not attempt to establish them quantitatively.

?? demonstrates the effect of eccentric viewing on the subjective appearance of motion in the display. Two "wheels" are shown, each containing five moving elements. Each element has a short range motion, and a long range displacement. In the wheel on the right, the direction of short-range and long-range components is in agreement (both counterclockwise) whereas for the wheel on the left, the short range component is clockwise while the long range component is counterclockwise. What is striking in this display is that its appearance changes depending on the viewer's gaze. With the eyes fixated on the point in the center of the left wheel, the elements on both wheels appear to orbit counterclockwise. But if gaze is focused on the right wheel, the left wheel now appears to rotate counterclockwise.

??shows only one element in each circle, but is otherwise identical to**??**. In this case the direction of gaze does does not cause a change in the perceived direction of motion of the element on the left. Therefore it would appear that it is not just eccentric viewing that causes short range motion to dominate over long range, but also the *density* of the elements in the stimulus.

Taken together, these demonstrations motivate our investigation of the interplay of three factors in determining motion perception: the agreement of short-range and long-range movement, the eccentricity of the stimulus, and the density of elements contained therein.

The primary phenomenon we will be exploring in this paper is the density-driven reversal of the apparent direction of motion that occurs in incongruent stimuli (those whose short range and long range components are in opposition.) When elements are widely spaced, the perceived direciton of motion typically follows that of the envelopes; as element spacing decreases, the perception of motion instead agrees in direction with the carrier.

We will proceed to quantify this reversal effect below. In order to do so we ask subjects to make forced classifications of the stimulus' overall direction (clockwise or counterclockwise.) However, the subjective appearance of our stimulus can be complex, with several properties that change aside from overall direction. Although we do not attempt to quantify these details of the appearance of our stimuli, we feel it is worth describing our impressions of them. Suitable individual adjustments of element spacing and other properties appear to elicit the same kinds of descriptions in everyone we have shown these stimuli to.

When elements are closely spaced, it is generally impossible to see the direction of envelope motion; the overall impression is of motion the the direction of the carrier. However, the amount of subjective flicker does appear to differ between incongruent and congruent motion, with ingongruent motion having more flicker.

Increasing the inter-element spacing somewhat, we approach a critical spac-

(a) When fixating at the center of the left wheel, both wheels appear to move in the same direction. But when fixating the center of the right wheel, both wheels appear to move in opposite directions. The appearance of the right wheel's movement reverses depending on the viewing eccentricity.

(b) Same stimulus as**??** with only one element used in each. The perceived direction of motion is independent of eccentricity.

ing, where for incongruent stimuli, subjects equivocate in their reports of perveived motion direction, The subjective appearance of a critically spaced, incongruent motion stimulus is somewhat variable. To some observers, it appears to first move in the direction of the carrier, and then to reverse direction shortly after stimulus onset. Although both the carrier and envelope motions are (considered separately) consistent with an underlying rigid rotation of a surface around the fixation point, or alternately a rotation of the observer, the perception does not appear to obey a rigid body constraint; elements can appear to move clockwise in some parts of the circle and counterclockwise elsewhere. Nor is the perception of movement bistable; a change in perceived direction for some element of the circle does not, in general, cause the perceived motion of the entire stimulus switch direction. Attention does play a role; for incongruent displays with closely spaced elements, it is possible to direct attention to one (or sometimes several) elements in the circle; these elements are seen to move in the direction of envelope motion, but the rest of the circle is seen to move in the contrary direction, making for a somewhat paradoxical percept wherein movement is in opposite directions, but individual elements are not seen to cross over or collide.

Increasing the spacings further to where element motion tends to dominate, observers often describe the motion contained in the stimulus as belonging to two components, one belonging to the motion of the elements themselves, and the other being a kind of "wind" overlaid on top of the elements. This seems similar to the perception elicited by a moving grating superposed on a stationary pedestal (**?**).

At even wider element spacings the envelope motion dominates the perception. It becomes difficult to even tell the direction of motion of the carrier, apart from the amount of flicker. That is, the "wind" seen at slightly smaller spacings becomes less evident. This "capture" phemomenon was characterized by Hedges et al. for single element stimuli constructed similarly to ours.

The subjective speed of the elements also changes with the element spacing. As element spacing is reduced, the perceived speed of element motion (as distinguished from the "wind") also seems to reduce, until spacing near the critical distance, where the elements almost appear to be at a near standstill over the brief duration of the stimulus.

Thus at very narrow and very wide element spacings it becomes difficult to tell congruent motion apart from incongruent motion via the sensation of motion direction. However, the sensation of subjective flicker and smoothness of movement does tend to tell the two stimuli apart. Incongruent stimuli have more flicker, at both narrow and wide element spacings, and appear to move less smoothly. We have attempted to correlate this sensation of smoothness or lack thereof with reports of the instantaneous position of the elements, without success.

As a final note, in some instances it appears that small fixational eye movements have some influence over the appearance of these stimuli. This is most easily demonstrated in a where the long range displacement is zero but the carrier has a consistent direction, as shown in **??**. Viewing this stimulus with the

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Figure 3: The timecourse of the task.

elements in the periphery, one sees a counterclockwise motion of the stimulus, which appears to fade and slow over time. Hovever, large or small saccades seem to re-awaken the movement, causing it to speed up again. The impression is similar to that seen in versions of the peripheral drift illusion, such as the "rotating snakes" illusion of Kitaoka (?). However, while perceived motion in the peripheral drift illusion appears to be driven by slight shifts of a stationary image on the retina, the construction of our stimulus would tend to rule that out as a mechanism; the motion is directly contained in the stimulus.

4 Experiment 1

The demonstrations in?? and ?? seem to suggest that the perceived reversal of motion direction is a function not only of eccentricity viewing but of an interaction between multiple moving elements. We explored this spatial interaction by varying the distance between elements that were moving at a constant eccentricity.

4.1 Methods

Observers viewed stimuli at four different eccentricities (2.96, 4.44, 6.67, and 10.00°), with parameters as described in ??. Elements were spaced evenly around a circle surrounding the fixation point; therefore varying the spacing of the elements is equivalent to increasing the number of elements in the stimulus. We ued the method of constant stimuli. The stimulus in each trial with equal probability contained either congruent, incongruent, or counterphase motion elements, with the direction of long range motion being with equal probability clockwise or counterclockwise. The set of element spacings was chosen to cover the psychometric function for each observer, based on preliminary sessions. Data shown is an aggregate of multiple sessions (at least 3 for each subject).

4.1.1 Task

The timecourse of a trial is illustrated in ??. A fixation point was presented. The computer then waited for the observer to fixate. 250 ms after detecting fixation, the motion stimulus was shown. After the motion stimulus concluded, observers indicated the direction of perceived motion by turning a knob.

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Figure 4: Percieved direction of motion as a function of inter-element spacing. The vertical axis plots the proportion of responses where the percieved direction of motion agrees with the long-range component of the motion stimulus. The horizontal axis the spacing between elements, in visual arc. Stimuli plotted here were presented at 6.67 degrees eccentricity. Only responses that fall within the time window are used in the computation of response rates.

Observers were required to maintain fixation during the motion stimulus. If subjects blinked or broke fixation before the offset of the motion stimulus, the trial was aborted and reshuffled into the stimulus set to be repeated later in the session. Observers were also required to respond within a fixed temporal window. Response latency was defined as the elapsed time between motion onset and the knob being turned. If the response latency was more than 550ms or less than 1050ms, subjects received visual feedback that their response was either too fast or too slow, and the trial was reshuffled into the stimulus set to be repeated later in the session.

For congruent and counterphase stimuli, subjects received audio feedback immediately after they gave a response, in the form of a high or low tone depending on whether their responses agreed with the direction of long-range motion. For incongruent stimuli, a neutral click was given as feedback instead of a tone; observers were told that there is no "correct" answer for those stimuli. This audio feedback seemed to help subjects establish a rhythm through the experiment.

Although we are most concerned with the appearance of incongruent motion stimuli, we used an equal proportion of congruent, counterphase, and incongruent stimuli in all experiments. We felt this was necessary to verify that observers were judging the long range motion component of the stimulus, rather than developing alternate strategies (such as simply countermanding the perceived short range motion.)

Subjects performed the task in sessions of at most 1 hour, divided into 4 to 6 blocks of 150 to 200 trials each, and were prompted to take a break between blocks. Subjects could also rest at any point by simply delaying fixation. At the beginning of each block, the eye tracking system was automatically recalibrated by asking the subject to make saccades to a sequence of targets at randomly chosen locations on the screen.

4.2 Results

4.2.1 Element spacing drives the perceptual reversal of perceived direction for incongruent stimuli

Here we display only the data from the 6.67° eccentricity. In **??**we fold together clockwise and counterclockwise motions and compute the proportion with which the overall motion was perceived to be in teh same direction as the actual enve-

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Figure 5: Responses to incongruent stimuli are color-coded according to whether the responses agree with the direction of long-range motion. All responses are shown, including those falling outside of the response time window, and those from sessions enforcing a more permissive time window.

Figure 6

lope motion. This proportion is plotted as a function of inter-element spacing for each of the three motion types (concruent, incongruent, and counterphase.)

The main effect evidenced is for incongruent motion, where the direction of short-range motion is opposite that of the long-range motion. At large inter-element spacings, observers judged the stimuli to move according to its global direction of motion. However, as inter-element spacing decreases,

For congruent motion, as expected, subjects are able to judge its motion nearly perfectly. For counterphase motion, however, there is a trend for increased errors at smaller spacings.

4.2.2 Critical spacing

We fit cumulative logistic functions to subjects' responses, which are overlaid on**??**. For robustness, we fixed the lower asymptote, corresponding to responses in the direction of short-range motion at 10% and the upper asymptote, corresponding to responses in the direction of long-range motion at 95%. This curve fitting was implemented as generalized linear model, with binomial errors and an inverse link function corresponding to a modified logistic curve scaled to have the chosen asymptotes. We define the critical spacing to be where the fitted curve crosses 50%; this is indicated in the graph with horizontal error bars. In all subjects this critical spacing

4.2.3 Dependence on response time

Some observers' responses varied with their response time. In **??**, we show an aggregate of all data including data which fell outside the response time window. Each trial is plotted as a single point, color coded according to whether the observer judged the subjective motion to be inagreement with the stimulus' short-range motion or with its long-range motion (only data from incongruent motion trials is shown, so these possibilities are mutually exclusive.) Points are horizontally jittered to avoid overlap; we only tested discrete values of element spacing. What is evident is that there is not only a dependence on the target spacing, but for two subjects (D.A. and J.T.) there is also a dependence on response time. For fast trials where obervers responded sooner than about 400 ms from motion onset, most responses agreed with the short-range component of the motion stimulus. But for longer response times, observers tended to agree with the

These observers' verbal descriptions of the stimulus tended to agree with this temporal depencence. Observers reported that some stimuli started with an apparent motion in one direction, but then the direction appeared to reverse. Another frequent report was a sensation of second-guessing oneself after giving an initial response.

There may be a number of resons fot this dependence on response time. It may be due to a longer time required for the long-range motion system to activate and may also simply be due to the fact that information about short-range motion is present in the stimulus slightly earlier than information about long-range motion (as the direction of long-range motion is only established when the envelopes have been seen at two locations,) although there was not a strong tendency for observers' responses to counterphase motion trials to change as a function of response time. Information about short and long-range motion may be integrated in a desision process which favors long-range motion as more information is gathered. Or other cues such as flicker may be involved. However, there was not a tendency for observers to change their reponse times as a function of element spacing, or other physical properties of the stimulus. For the purposes of investigating the effect of element spacing, we set a 500 ms wide window beginning 400 ms from motion onset, for this and further experiments. Subjects received feedback for whether their responses fell in this window

4.3 Change in spacing with eccentricity

5 Experiment 2

5.1 Methods

5.2 Results

6 Experiment 3

In **??**we saw that the perceived direciton of motion appears to be dominated by the short-range motion content when the distance between features is smaller than some critical distance, and by long-range movement when spacing is larger than that critical distance. **??**showed that this critical distance scaled in a roughly linear fashion with the stimulus eccentricity. However, because the stimulus consists of a number of elements spaced evenly around a circle, a linear dependence of critical spacing on eccentricity would imply that the critically spaced stimuli contain approximately the same number of elements at all eccentricities tested (**??**). So an alternate way of describing the results of **??** would be to say that the perceived direction of motion is dominated by short range information when the elements in the display are more numberous than some threshold.

(a) Response rates for incongruent stimuli for each subject. Element spacing is plotted on the horizontal axis, and is plotted on the vertical axis. Colors indicate stimuli tested at different eccentricities.

(b) Horizontal intercepts are computed and shown with standard errors.

Figure 7

Several studies of the "multiple object tracking" task (cites: Pylyshyn et al.) have shown that when attentively tracking a subset of objects moving among distractors, there appears to be a limit of the number of objects tracked.

Furthermore, the short range and long range motion systems may respond differently to our stimuli as a function of the number of targets rather than their spacing. For eample, there may be a process that integrates short range motion over the entire visual field, such that stimuli containing more motion energy (by virtue of a greater number of identical targets) would result ina greater influence of the local motion content over the global. For example, optic flow may be computed by integrating short-range motion signals over the visual field; adaptation to optic flow stimuli confined to one part of the visual field results in adaptation effects on non-overlapping parts of the visual field (cite); our stimulus is configured in a manner that the short range motion is consistent with the optic flow resulting from a rotation of the observer.

Therefore we wished to know whether the apparent reversal of the stimulus as target spacing decreased could have been an effect of the number of targets increasing.

6.1 Methods

The task was identical to that in **??**and**??**. The stimulus was fixed at 6.67 degrees eccentricity. The stimulus consisted of a number of moving elements, identically specified to those in **??** but instead of being evenly distributed around a circle, the elements were limited to a region on either the left or right side of the display. We varied both the spacing and the number of elements used; accordingly, the total spatial extent of the stimulus varied from trial to trial. The values of spacing and element count we used are shown in **??**. Each value of element spacing was tested using more than one value for the element count, and vice versa.

When only displaying the elements confined to a segment of the circle, it is easy to discern the direction of motion by noting the change in position of the elements. at either end, or by treating the entire set of moving elments as a group and noting the change in position of its boundary. To remove this endpont cue we added two non-moving flanking elements towe the stimulus, at either end of the group of moving elmeents. The flanking elements flickered in counterphase identically to those used in counterphase stimuli in **??**. On all trials, the flanking elements were positioned so that they were 1° away from the adjacent moving element at its closest approach (which occurred at either the beginning or end of the stimulus, depending on the direction of motion.) The angle formed by the two flankers was at least XXX and no more than YYY degrees. Note that the spacing between these flankers and the adjacent moving elements are constant for all values.

When viewing the full circle stimuli of **??**, observers were free to direct their attention to any region of the screen they wished to, as long as they held fixation at the central point; it is possible that observers were attending to a smaller region of the circle in the process of discriminating elment motion. [Preliminary

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(a) Data from ??are re-plotted to show the number of elements present in the stimulus at PSE. The number of elements in the screen at PSE is relatively constant across eccentricities for each subject.

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(b) Stimulus diagram. A number of moving elements are present on either the left or right sides of the display. Two additional flanking elements (marked *) are added. The flanking elements are positioned 1° away from the adjacent elment at its closest approach.

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(c) The set of stimuli used in this experiment. The number of elements used and the spacing was tested at each combination used

Figure 8: Format of density/number experiment.

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(a) Raw data from subject DA. In the left axes, the proportion of responses agreeing with global motion is plotted as a function of the number of moving elements in the stimulus. Data is grouped according to the element density and separate lines are drawn for each element. On the right axes, the proportion of responses to global motion is plotted as a function of the element density, with data grouped by the number of moving elements.

[[Image Discarded Due To

(b) Logistic regression coefficients for
regression was used to apportion sub
helement spacing. Positive values for
of responses agreeing with local motio
number constant; vise versa for the co

Figure 9: Results of density/number experiment.

experiments suggested that observers were less accurate in detecting long-range motion when they could not anticipate the region of the display where stimuli were to appear.] Therefore to provide the most direct comparison to??, we centered our stimuli on the left and right sides of the screen, in alternating blocks, allowing observers to anticipate the location if the stimulus without switching attentional loci between trials. We anticipate that some subjects may have anisotropies in the visual field, leading to different values of the critical spacing (or critical element count) in different parts of the visual field; this has been observed both for critical spacing in crowding (ref...) and for target count as in MOT experiments (ref...). Four examples of the flanked stimuli are shown in Movie 2

6.2 Results

7 Changes in stimulus size

8 Discussion

We should discuss the ways in which this stimulus differs from crowding (and yet, how the phenomena are similar.) Draw the connection between "feature spread" and crowding. I.e. Several studies have

First there is the question of what kind of motion system the long-range component is engaging. We have tried to avoid the tempting terms "local" and "global" to describe the two

Another form of large-scale integration of short range motion occurs in the computation of optic flow, which term describes a pattern of motion over the entire visual field that is consistent with being generated by the motion of an observer through the environment, opposed to the motion of objects relative to a stationary observer. The simplest examples of optic flow stimuli are patterns such as global expantion or contraction, or rotation around a central point. The patterns of motion that in our motion illusion are consistent with a rotation around the axis parallel to the viewer's gaze, so an optic flow mechanism is likely being driven my our stimulus. This raises the question of whether optic flow mechanisms are involved in the illusion of reversal. [some sense of] However, [no second order global motion] [our experiment on number versus shape] [however we found that...]

In the monkey, it appears that [the dorsal subdivision of] area MST is specialized for optic flow patterns.

8.1 Classification of this stimulus among the various types of motion stimuli

Some models for detection of non-luminance-defined motion posit a mechanism that operates much like first-order, short-range motion, but applies some (space-time separable) nonlinearity to the image before applying the motion energy analysis. This would be called "second order" motion system in the scheme of **?**. We noted in**??**that for a lone element, it is more difficult to discern the direciton of its short-range motion than the clear long-range movement. By adjusting the parameters to further favor the long-range component, we can produce stimuli where the direction of the short-range motion is nearly undetectable, yet these stimuli still elicit a motion after-effect according only to the direction of hort range motion. Nonetheless, these stimuli still elicit a direction-elective response in area MT only to the short-range component(**?**). motion and independent the direction of long-range motion. Thus, while the have added have quantitatively demonstrated the presence of this phenomenon, which they term 'motion capture.' That is, the long-range motion is capable of masking and obscuring short range motion. Additionally, a mechanism driven by a single input nonlinearity (and in some formulations, any purely local mechanism (**?**) would be driven by first-order motion stimuli as well as second-order; this is consistent with results showing that adding second-order noise, or even coherent second-order motion, does not interfere with the decection of first-order motion, but first-order noise does interfere with detection of second-order motion (**??**). However, this behavior is not consistent with our separate long-range and short-range motion; local motion opposes it. So while a second-order mechanism seems to exist and is able to detect some forms of non-Fourier motion, we do not think a second-order mechanism plays a significant explanatory role in our illusion and is not responsible for the illusory reversal.

?investigated crowding for discrimination of moving objects in a variation of the typical crowding task where targets and flankers moved around an annulus. They found that the size of the region of interference between the target and a lateral flanker was invariant with target speed (if anything, there was a maximum at 2-4 "angular degrees per frame" (at 75 Hz; at 8 degrees ecentricity, 2 degrees per frame ~21 degrees-of-visual-angle per second. That's a lot faster than out stimuli.) They did find that the zone of interference around a moving target was asymmetric contingent on motion; a flanker moving ahead of the target crowded at a greater distance than a flanker that trailed the target. If this were simply due to temporal summation (i.e. motion blurring,) "we would expect crowding to increase with speed because motion blur increases with speed of sharp objects"

?show that crowding applies to the identificaiton of direciton of motion of a textured patch within a window. Since the stimulus in that study does not include a global direction component, it is not (all of our local motion features are identical.) Actually the format of this study shares many similarities to our own, but what they establish is the spatial interference of flanking (short-range) motion on identification of neighboring patches of (short–range) motion, wherewas what be identify in this study is the interference of flanking (short-range) motion in the identification of (long-range) motion – this is an interesting distinction, as it shows that spatial interference happens in a way that prevents