Supplemental Information for:

Flexible Retinotopy: Motion Dependent Position Coding in the Visual Cortex

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Materials and Methods

Eight subjects participated in the functional imaging experiments, including two of the authors. Scanning protocols were approved by the University of Western Ontario Human Subject Review Board. Each participant's inion was rested above a two-element radio frequency (RF) surface coil. Braces and padding on the side and forehead of the participant restricted head motion and provided feedback to the subject about any body movements. Stimuli were back-projected with a projector (60 Hz) onto an opaque screen from outside the bore. A mirror directly above the subject provided a reflected view of the stimuli. Viewing distance was 25 cm. Subjects fixated on a bull's-eye on a grey background at all times. In the main experiment there were four stimulus conditions, each of which contained four patterns (sinusoidal luminance modulations with a gaussian envelope, ~2.9 deg standard deviation, ~0.2 cycles/deg, 90% contrast, ~13 deg eccentricity). The four patterns (examples shown in Fig. 1) contained motion either toward or away from the fovea (~2.5 Hz) or were stationary or flickering (~8 Hz). The positions of the four patterns (i.e., the stationary gaussian envelopes that defined the borders of the patterns) were physically identical in all four stimulus conditions.

Imaging was done on a 4-Tesla whole-body system. A four-shot interleaved, blipped EPI sequence was used to collect T2*-weighted images over each 320 s run. The functional images were collected with centric-ordering of k-space and navigator-echo correction. Parameters: TR = 2000 ms, TE = 15 ms, FA = 30 deg, FOV = 19.2 x 19.2 cm^2, voxel size = 1.5 x 1.5 x 2.5 mm^3, 8 slices per volume, 160 volumes. The imaging volume was parallel to and centred on the calcarine sulcus.

In the first experiment, four stimulus conditions (i.e., patterns that moved inward, outward, flickered, or were stationary) were randomly interleaved in a block design. Each functional run consisted of four conditions presented to the subject eight times each

(10 s each). Subjects were instructed to press a key each time they perceived a shift in the eccentricity of the four patterns. Subjects participated in a minimum of eight functional runs. At the beginning of each subject's functional session, a reference anatomic volume (1 x 1 x 1 mm^3, MP-FLASH sequence, T1-weighted) was acquired in the same orientation as the functional data. This anatomic volume was used to align the functional data with a high resolution (1 x 1 x 1 mm^3) T1-weighted anatomic volume imaged in a separate session with an RF head coil. An affine transformation was applied to precisely align the surface coil data to the head coil anatomic volume (by means of blink comparison and image intensity subtraction). The cortical surface of each participant was reconstructed from the head coil volume.

Brain Voyager software was used at all stages of the data analysis and cortical reconstruction. Images were high-pass filtered (components that occurred three or fewer times per run were removed) and a correction for serial correlations was used for all analyses. A minimum cluster size of 18 voxels was used to correct for multiple comparisons, yielding a whole brain corrected threshold of $P < 0.001$, as determined by AlphaSim (B.D. Ward, http://afni.nimh.nih.gov/afni/docpdf/AlphaSim.pdf; 10,000 simulations with a brain volume of 131,072 voxels and single voxel threshold of $P < 0.05$).

Control experiments employed identical methods, but the stimuli varied. In one control experiment there were three stimulus conditions. In two of these conditions, four flickering patterns were presented at either ~12 deg or ~14 deg eccentricity. In a third condition, stationary patterns were presented at ~13 deg eccentricity. The three stimulus conditions were randomly interleaved in 320 s functional runs. In a second control experiment, the same stimuli from the main experiment were used, but the inward and outward motion was presented at ~10 Hz. In a third control experiment, similar moving gabor stimuli from the first experiment were presented, but rather than having a blurry aperture, the edge was sharp (see Fig. S6.A, for an example); the contrast of the envelope of the gabor was a square wave rather than a gaussian. In a fourth control experiment, there was an attentional task presented at the fixation bull's-eye. The gabor stimuli were identical to those in the third control experiment. Superimposed on the fixation bull's-eye was a disk that intermittently flashed either red or blue randomly. Subjects were instructed to count the number of colored flashes that occurred over the course of a trial (10 s) and determine whether there were more red or blue flashes. The colored flashes were presented at ~1 Hz, and were presented continuously until ~500 ms before the end of each trial. In a fifth control experiment, a radial grating (windmill) was divided into four quadrants. The radial grating (~30 deg diameter) consisted of 8 cycles per rotation at 97% contrast on a black (1 cd/m^2) background. The upper left and lower right quadrants contained a grating that rotated in one direction (either clockwise or counterclockwise, ~4 Hz), while the other two quadrants contained motion that rotated in the opposite direction. The vertical and horizontal meridians of the stimulus (and the visual field) therefore contained a trailing edge (origin of motion) and a leading edge of the moving pattern, respectively, or vice versa (see Fig. S6.C, for an example). In a sixth control experiment, we measured the retinotopic boundaries between V1 and V2. To do this, we presented flickering gabor stimuli (identical to those in first experiment, but with a hard aperture) in opposite quadrants of the visual field (upper right and lower left or vice versa). There were three conditions in this experiment: in two of the conditions, the flickering gabors were presented, and in a third, only a fixation point was visible (providing a baseline).

In the first psychophysical experiment, we measured the magnitude of the illusory position shift that occurs on the moving gabors. Stimuli were presented on a CRT monitor. Subjects were seated 32 cm from the monitor (85 Hz) and fixated on a bull's-eye at all times. Stimuli were similar to those in Fig 1, the first imaging experiment.

Each gabor was ~20 deg maximum diameter, 2 deg standard deviation, and 97% peak Michelson contrast. The carrier translated at 2.5Hz and was ~0.2 cycles/deg. To measure the magnitude of the illusory position shift, two patches (like those in Fig. 1) in the right visual field contained motion in a direction opposite that of the two patches in the left field. When stationary, the patterns appear to lie at the four corners of an invisible square; when the patches contain motion, however, they appear shifted in position, creating an illusory chevron shape. The physical displacement in the positions of the four patches that nulled this illusion was measured in a 2AFC method of constant stimuli experiment (the patterns were physically displaced by one of six magnitudes, and subjects reported the direction of the illusory position shift; a logistic (psychometric) function was fit to the data, where the 50% point on the function indicates the point of subjective equality (PSE)—the cancellation point (*1*)). The apparent position shift found here was used in the second experiment as the separation between the physically displaced flickering patterns.

In the second psychophysical experiment, we measured the perceived shift in the position of the trailing and leading edges of the gabor patterns independently. Stimuli were presented on a CRT monitor. Subjects were seated 57 cm from the monitor (75 Hz) and fixated on a bull's-eye at all times. Stimuli (shown in Fig. S4) were similar to those in Fig 1, except that each gabor was windowed on three sides to remove any illusory position shift. The top edge remained blurred. The gabor of interest was oriented vertically and the comparison gabor was oriented horizontally. Each gabor was 6.6 deg maximum height, 3.8 deg width, 1.4 deg standard deviation, and 97% peak Michelson contrast on a grey background (38.9 cd/m^2). The carriers of both gabors translated at ~3 Hz, and were each ~0.33 cycles/deg. The top edge of the comparison gabor did not appear shifted as a function of the motion of its carrier. The comparison gabor could be located to the right or left of the test gabor, determined randomly on each trial. The direction of motion was also random on each trial. In the experiment, the vertical positions of the two gabors were offset in opposite directions by one of six values. In a 2AFC task, subjects reported which gabor appeared taller (higher). The method for calculating the PSE was the same as that described above. The PSE indicates the physical shift in the positions of the gabors to make them appear aligned (of the same height). In one control experiment, the fixation point was located near the top or bottom of the gabor. In another control experiment, the two gabors contained motion on a random walk schedule; the direction of motion in each gabor was independently and randomly determined every 27 ms.

The third psychophysical experiment was identical to the previous one, except that rather than systematically varying the horizontal position of the gabor, we varied the standard deviation of the gabor's (gaussian) envelope. Note that the gabors were all windowed on three sides, so the gaussian luminance contrast profile only applies to half of the gabor. The physical luminance contrast profile of each gabor was gaussian with a standard deviation of 1.4 deg. We varied the standard deviation of the comparison and test gabors in opposite directions and measured the PSE (i.e., the difference in the standard deviation of the two gabors that created an apparent match). The direction of motion, relative position (to the left or right of fixation), and standard deviations of the envelopes were randomly determined on each trial.

The fourth psychophysical experiment measured the degree of induced motion that occurred at the trailing and leading edges of a moving pattern. The central pattern was 14.9 deg width, 3.8 deg height, ~0.33 cycles/deg, translated at ~9 Hz, and had a sinusoidal luminance modulation of 97% contrast. There were two patterns presented in the surrounding region, one at the leading edge of the moving pattern and a second at the trailing edge. Both patterns were identical. Each pattern as a whole was ~3.8 deg in height and 5.7 deg maximum width. The luminance contrast of each flickering pattern was abrupt on three sides; the fourth side (the outer edge) had a gaussian luminance profile with a standard deviation of 2.0 deg. Each pattern consisted of 6 interleaved horizontal sinusoidal luminance modulated gratings (33% base Michelson contrast). Each of the interleaved gratings was ~0.4 deg high, had a temporal frequency of 1.5 Hz, and a spatial frequency of ~0.33 cycles/deg. Three of the interleaved gratings translated leftward, while the other three translated rightward. When the luminance contrast of the left and rightward moving gratings is equal, they appear to flicker; the motion is balanced. Increasing the contrast of the gratings moving in either direction biases the perceived motion of the flickering pattern, as a whole, in that direction. When the central coherently moving pattern contains rightward motion, the flickering pattern appears to move in the opposite direction (induced motion). To measure whether the induced motion percept is stronger at the trailing compared to the leading edge, we increased the contrast of the interleaved gratings that moved in one direction, at both ends of the coherently moving pattern. For example, at the trailing edge of the rightward moving pattern, we increased the contrast of the rightward moving interleaved gratings (serving to *null* the induced motion), while at the leading edge we also increased the contrast of the rightward moving interleaved gratings (serving to *enhance* the induced motion). If the illusory induced motion at the trailing edge is stronger than that at the leading edge, then it would be necessary to increase the contrast of the rightward moving interleaved gratings on both sides of the coherently moving pattern. The relative contrast of the rightward and leftward interleaved gratings was set randomly in each trial at one of six values (within ~±10% Michelson contrast relative to the baseline contrast). In a 2AFC task, subjects reported whether the flickering pattern at the trailing or leading edge moved more to the right. A psychometric function, like that described above, was fit to the data to estimate a PSE. The PSE indicates how much additional contrast must be added to the rightward moving interleaved gratings (in the example above) to create an equivalent motion percept in the flickering patterns. The direction of the coherently moving pattern and the relative contrast of the interleaved gratings was random on each trial.

Supplemental Figure 1:

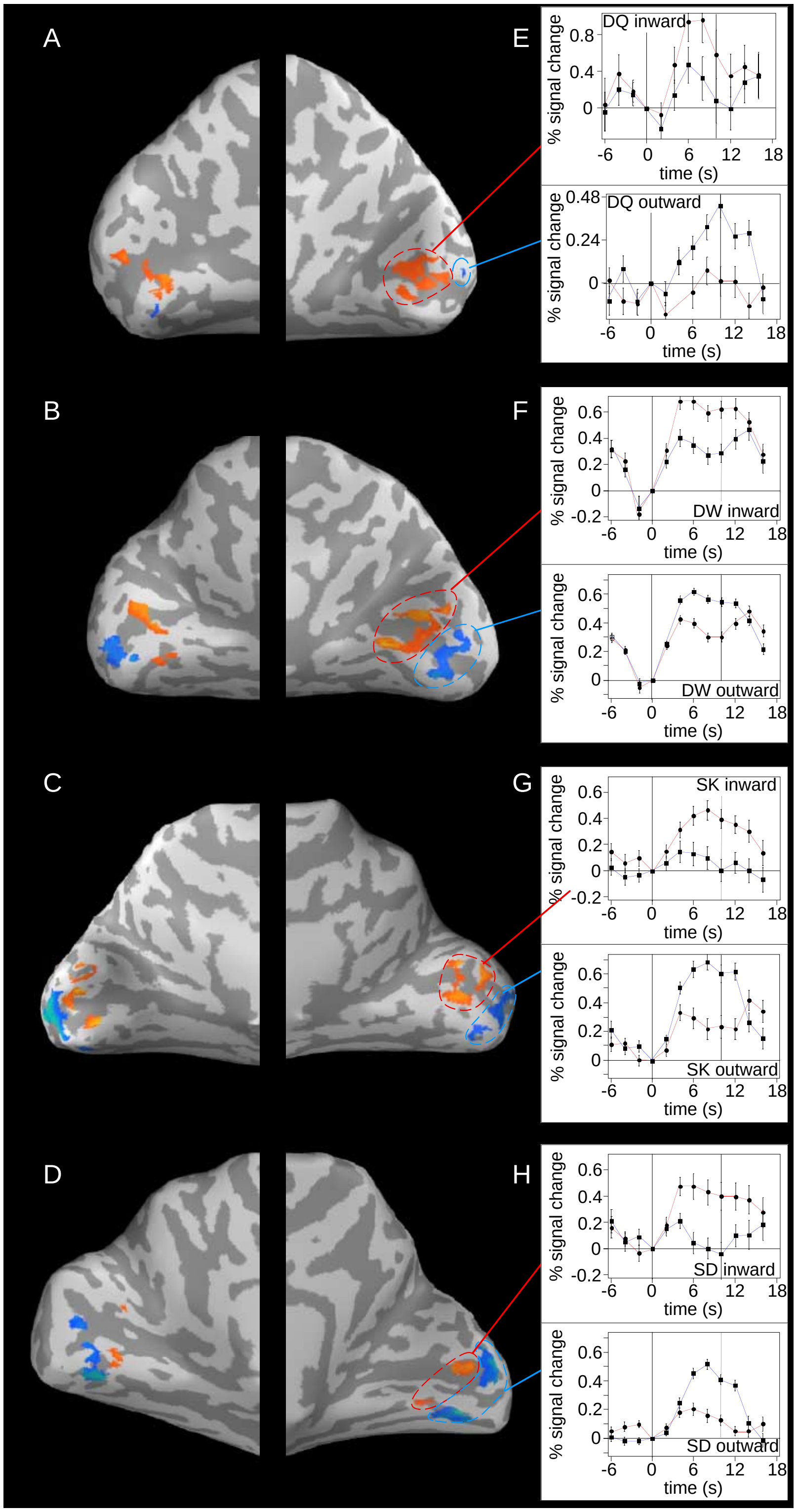

Figure 1S
Whitney, et. al., 2003

Fig. S1. Individual data for four subjects. **A-D**. Regions selectively activated by patterns containing inward motion (orange patches) and outward motion (blue patches) are superimposed on the cortical surface (see Fig. 1 for an example of the stimulus). Regions of activation produced by inward motion were located in more eccentric locations. Conversely, regions of activation selectively produced by outward motion were located in more central locations. **E-H**. The event-related averages for the regions of activity selectively produced by inward (orange patches) and outward motion (blue patches). The red lines indicate responses to inward motion, and the blue lines indicate responses to outward motion. Least significant difference in activation for inward and outward motion was for subject DQ, $P < 0.01$. Error bars, ±1 s.e.m.

Supplemental Figure 2:

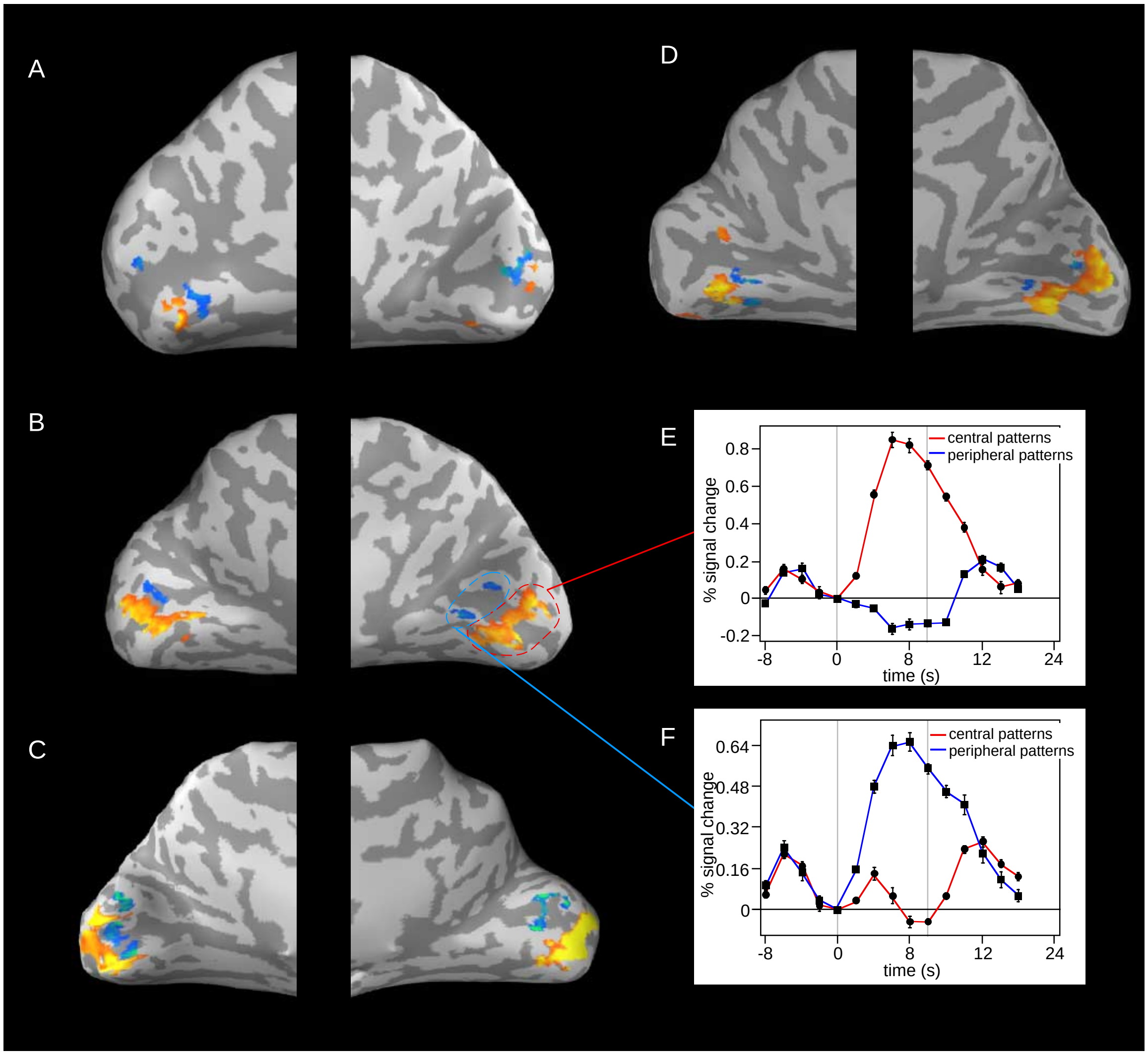

Figure 2S
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Fig. S2. Activation produced when the flickering patterns were physically displaced from 14 deg eccentricity (blue activity) to 12 deg eccentricity (orange activity). **A-D.** Results for the same four subjects as in Fig. S1. When the two conditions were subtracted, patterns presented more centrally produced selective activation (orange) that was closer to the occipital pole. This pattern of activation is expected from previous retinotopy studies(*2*,*3*), but is precisely opposite the pattern of results found in the first experiment. **E**. Event-related averages, for all subjects, for the regions of cortex that were activated by the central flickering patterns (orange activity on surface maps). **F**. Event-related averages for the regions of cortex that were activated by the peripheral (eccentric) patterns (blue activity). Error bars, ±1 s.e.m.

The results in the first experiment could theoretically have been caused by greater attention to the trailing edges of the patterns containing motion. However, attention to the trailing edges of the patterns is unlikely to have caused the results for several reasons. First, attending to one region of the visual field causes a decrease in the fMRI BOLD response to non-attended regions(*4*). We did not observe a negative BOLD response in any region in the first experiment, however (see event-related time courses in Figs. 2 and 3, and S1). The fact that we did observe a negative BOLD response to presumably unattended locations when the flickering patterns were physically displaced (**E** and **F**) suggests that, had attention been responsible for the results in the first experiment, we should have observed a similar negative BOLD signal (or at least a dip in the signal). Second, subjects were instructed to respond each time they perceived a change in the apparent eccentricity of the patches, a task that, if any attention were required, would lead subjects to attend to the apparent locations of the patches rather than blank regions of the visual field. Further, when asked after the experiment, subjects reported that they did not attend to the trailing edges of the moving patterns, and passive viewing is not sufficient to generate localized increases in activation with identical visual stimuli(*4,5*). We did, however, more closely examine the influence of attention in a subsequent experiment (see Fig. S7).

Supplemental Figure 3:

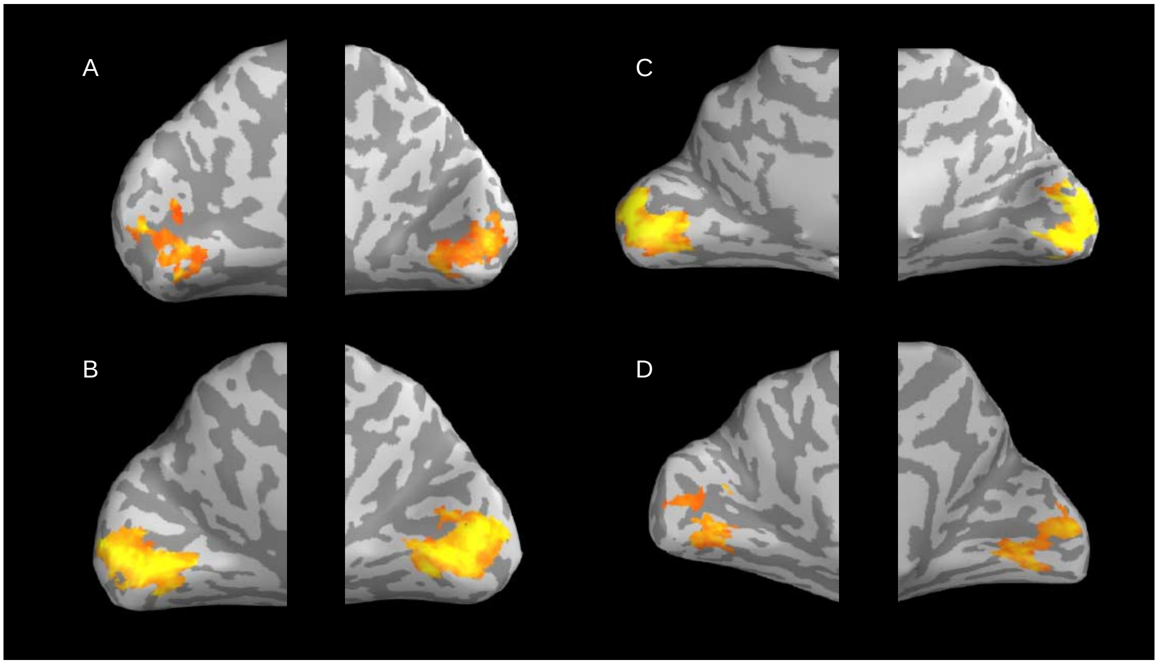

Figure 3S
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Fig. S3. Activation produced in the flickering condition for four subjects (the same subjects as Figs. S1 and S2). The patterns in the flickering condition were in precisely the same physical location as the patterns containing inward and outward motion. The activation produced in the flickering condition encompassed the regions of activation produced by the inward and outward motion conditions. That is, the activation shown here is a superset of the activation shown in Fig. S1. Note that the activation shown here is not the product of a subtraction (as all of the other activation maps show), but just the activity produced in the flickering condition relative to baseline.

Supplemental Figure 4:

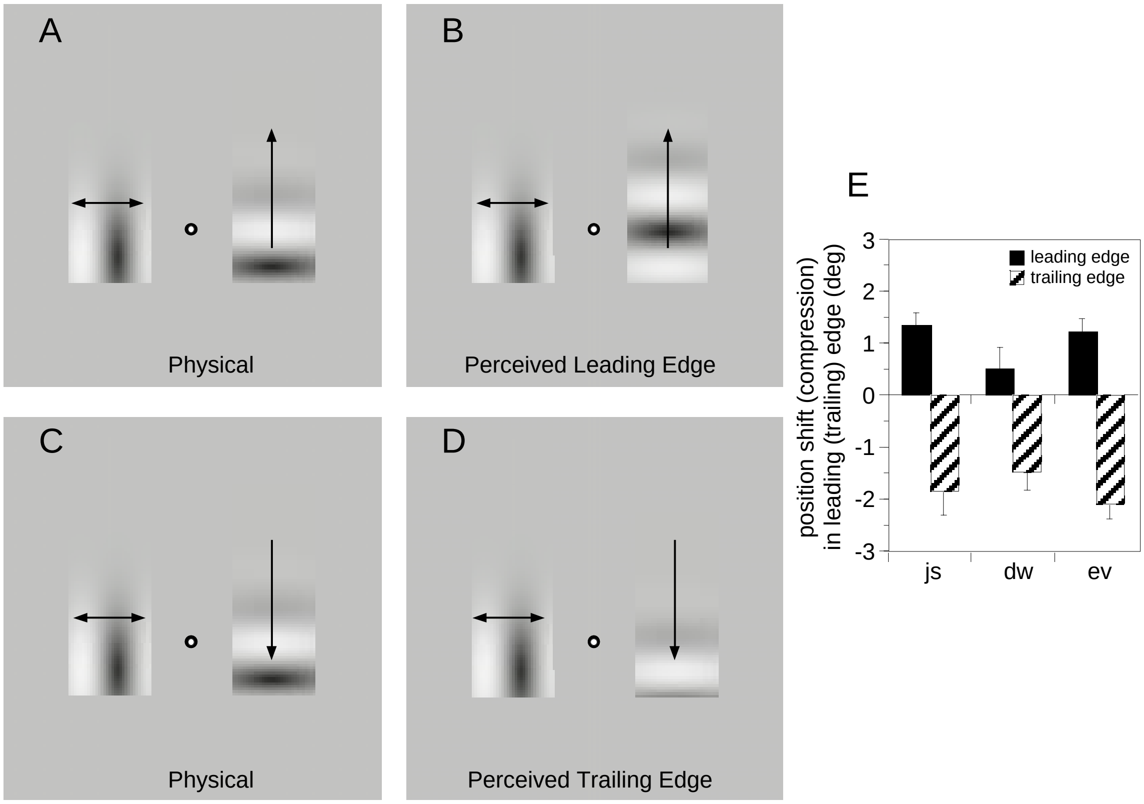

Figure 4S
Whitney, et. al., 2003

Fig. S4. Perceived shift in the size and shape of stationary patterns that contained motion, as measured psychophysically. **A**. The stimulus consisted of two patterns that contained motion, similar to those used in the first experiment (gabor patches that were, in this experiment, windowed on three sides; see Methods). Windowing on three sides allowed us to isolate the effect of motion on perceived position and its extent because there is no influence of motion on the perceived position of an abrupt luminance defined edge(*6*). The perceived positions of the windowed (sharp) edges therefore remained veridical while we measured the perceived size and shape of the one blurred edge. We were interested in the perceived size and shape of the pattern on the right. To measure this, we provided a comparison gabor (on the left hand side) whose orientation was rotated 90 degrees. This stimulus is useful because the leftward or rightward motion of the grating (carrier) does not influence the apparent position of the vertical edge that we were interested in (e.g., see ref (*7*)). As a result, the comparison grating is an objective measure of the perceived location of the envelope, without any confounding effects of motion direction. The comparison pattern on the left contained motion in either a leftward or rightward direction, randomly in each trial (we confirmed that there is no difference in the perceived shape of the envelope depending on whether the comparison motion is leftward or rightward). The pattern on the right contained motion that either moved upward or downward. In a 2AFC task, we measured the physical position of the pattern on the right that appeared to be of the same extent (height) as the pattern on the right (see Methods). **B**. When the pattern on the right contained upward motion, the leading (upper) edge of the pattern appeared shifted in the direction of motion (upward) relative to the comparison pattern. **C-D**. When the pattern on the right contained downward motion, the trailing (upper) edge appeared shifted or compressed in the direction of motion (downward). The question here is whether the magnitude of the illusory shift (or compression) is identical for the leading and trailing edges that are defined by upward and downward motion, respectively. If the carrier motion simply shifts the envelope in the direction of motion(*6,8*), there should be no difference in the displacement at the trailing and leading edges. **E**. Results of this experiment for three subjects. The solid bars show the shift in the perceived extent of the pattern when the motion was upward (upper blurry edge of the right-hand pattern in [**A**]). Similar to the data in Fig. 1E, the perceived position of the leading edge of the pattern appeared shifted in the direction of motion. The striped bars show that when the motion contained within the pattern moved downward, the apparent extent of the pattern—the trailing edge—was compressed. The interesting finding is that there was an asymmetry: the compression in the trailing edge (striped bars) was greater than the shift in the leading edge (solid bars).

Therefore, in addition to the known forward shift in the leading edge of the pattern(*6,8*), there must be an additional process that operates more strongly on the trailing edges than on the leading edges of the patterns, causing an illusory compression of the envelope. Clearly, the masking of the trailing edge does not explain why the leading edge appears shifted forward(*6-14*), but it partially explains the overall shift in the perceived position of the pattern and the pattern of activation that we found in the imaging experiments.

In one control experiment, we confirmed that the perceived size and shape of the patterns (the envelope) does not depend on the orientation of the carrier grating. If there was a systematic difference in the perceived shape and size of the patterns depending on the orientation of the carrier grating, this could explain our psychophysical results. We presented stimuli identical to those in (**A**), except that there was no coherent motion within the patterns—both patterns contained texture that moved on a random-walk schedule (i.e., the direction of motion was randomly determined every ~27 ms). We found that the perceived extent of the gabor’s envelope is slightly greater when the carrier grating is oriented vertically rather than horizontally, but this difference is not significant, and cannot explain the magnitude of the difference in (**E**) above. In an additional control experiment, we jittered the position of the fixation point (presenting it above or below the patterns) and found no difference in the results, showing that the effect is not due to an asymmetry between upward and downward motion. Error bars, ±1 s.e.m.

Supplemental Figure 5:

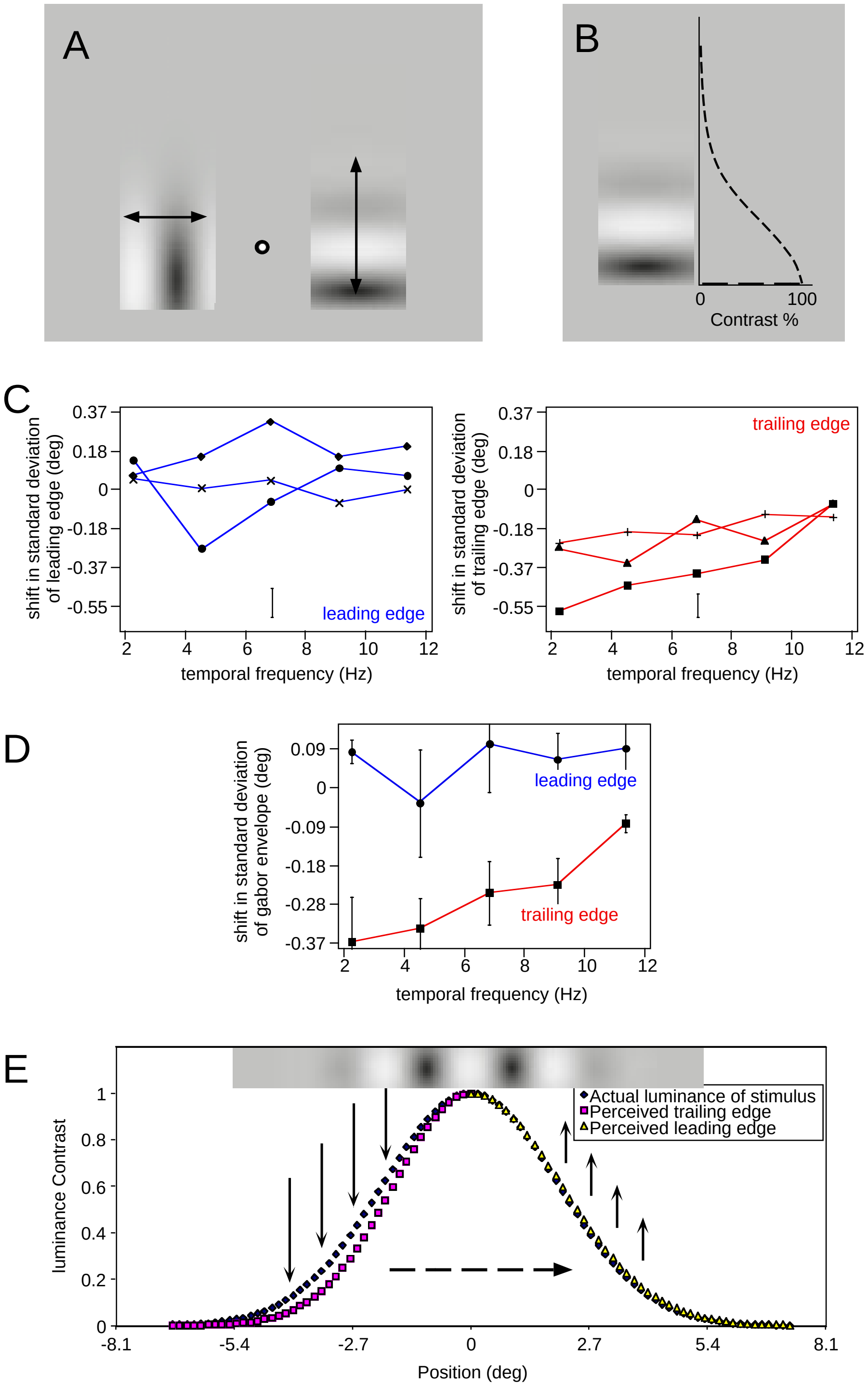

Figure 5S
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Fig. S5. Perceived distortion in the luminance envelope of the patterns that contain motion. **A**. The stimulus was similar to that described in Figure 4.S. Rather than shifting the overall position of the pattern (as in Fig 4.S), however, we measured the perceived luminance distribution of the gabors. To do this, we systematically varied the standard deviation of the gaussian envelope defining the pattern in a 2AFC task (see Methods). If there is a mechanism that operates selectively on the trailing edge of the moving pattern, we might expect to observe a difference in the perceived contrast (i.e., standard deviation) of the envelope at the trailing and leading edges. **B**. The luminance contrast of the envelope was normally distributed. **C**. Results for three subjects. The left-hand side shows that the perceived standard deviation of the gaussian envelope increases at the leading edge of the moving gabor. That is, positive values show that the contrast of the envelope was perceived to increase at the gabor's leading edge. The right-hand side shows that the perceived contrast of the envelope decreases near the trailing edge of the moving gabor. There is some indication that the effect varies with the temporal frequency of the motion; the data suggest that the illusion is more tuned to low temporal frequencies. It is worth noting, however, that the duration of each trial was brief in this experiment, ~500 ms. Representative error bars show ±1 s.e.m. **D**. The average data for the three subjects shows that there was a stronger effect at the trailing edge of the gabor: the reduction in the perceived contrast at the trailing edge exceeded the increase in the perceived contrast at the leading edge. To better visualize what this means, (**E**) shows a representation of the perceived envelope for one subject. The gabor stimulus is shown at the top of the graph for reference. The actual gaussian envelope of the gabor is shown by the blue diamonds (physically a normal distribution). The red squares represent the perceived envelope of the trailing edge, and the yellow triangles represent the perceived envelope of the leading edge. Clearly, the perceived contrast of the trailing edge is reduced more than the contrast of the leading edge is increased—suggesting a distortion in the apparent contrast of the gabor as a function of its motion. In Fig. 4.S., we found that the overall envelope at the trailing edge appeared shifted in *position* more than the leading edge. In this experiment, we found that the luminance contrast of the trailing edge is not just shifted, but also appears distorted. Error bars, ±1 s.e.m.

Supplemental Figure 6:

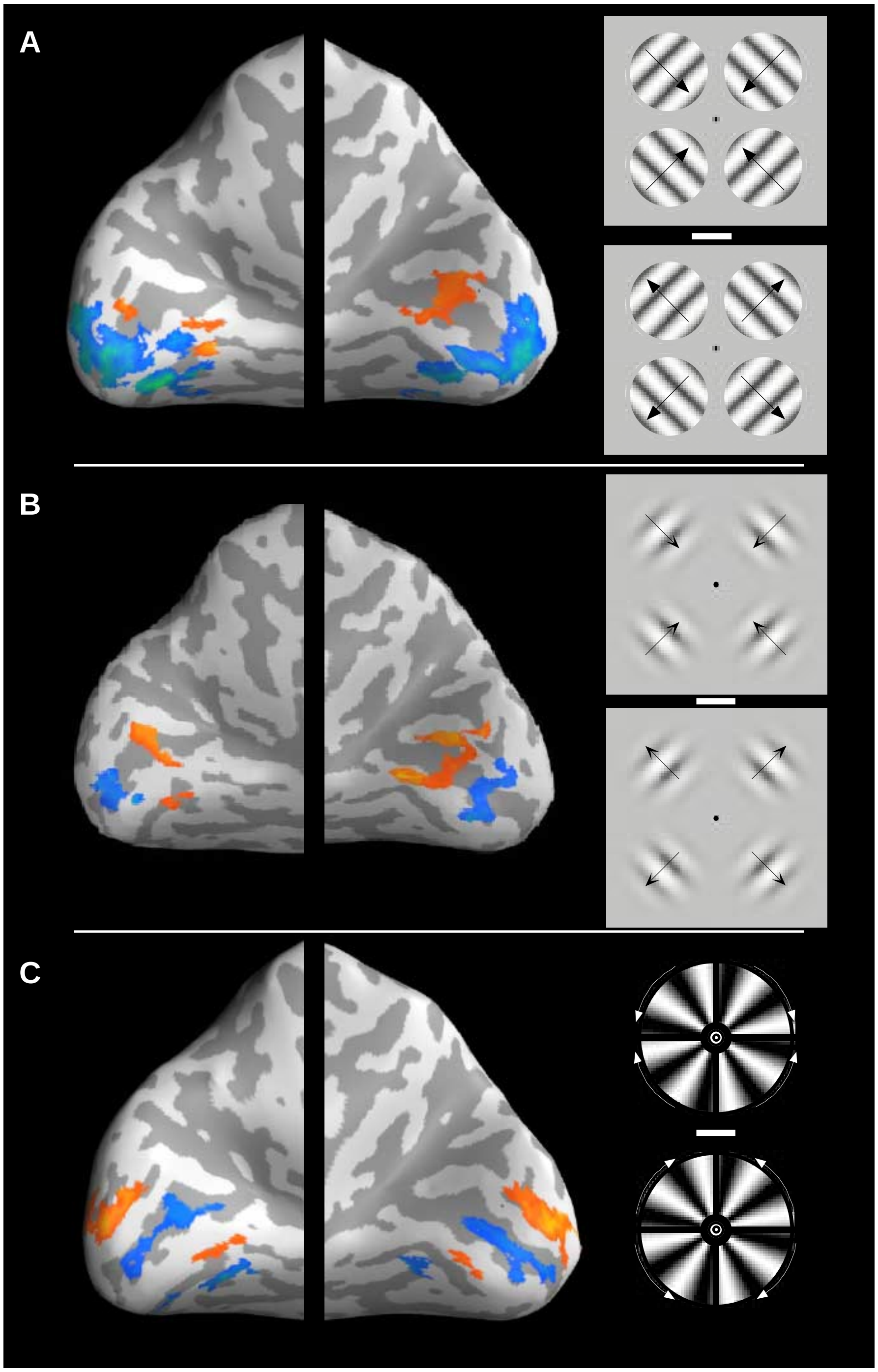

Figure 6S
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Fig. S6. Two additional control experiments. **A**. In one experiment, we presented patterns similar to those in the first experiment, except that the luminance contrast of the envelope's border was abrupt rather than gradual (gaussian). That is, the patterns containing motion had sharply defined edges. These patterns do not appear shifted in position. This experiment addressed two questions: first, is a blurry edge that is difficult to localize necessary to produce the pattern of activation that we found in the first experiment? And, second, is the pattern of activation that we found specific to an illusion of perceived position, or is it specific to the trailing edges of moving objects? We found that the pattern of activation in this experiment was identical to that in the first experiment. (The stimulus and pattern of activation from the first experiment are presented in **B**, for comparison.) The results show that the diffuse edge is not necessary, and, more importantly, show that peak fMRI activity does not correlate with shifts in perceived position; i.e., the perceived position of the patterns in the first experiment differs from the perceived position of the patterns in this experiment and, yet, the activation in V1 remains the same. The results suggest that the peak activation occurs closer to the trailing edge of moving patterns, regardless of perceived position. **C**. If the trailing edges of patterns that contain motion are really the important factor, then we should observe the same increase in activation at the trailing edge of any pattern containing motion. To test this, we presented four segments of a windmill that rotated toward or away from each other. We found that the peak activation always occurred near the trailing edge of the moving pattern, consistent with the previously described experiments. These results also rule out optic flow as a potential explanation for the pattern of activation. The activation is so precise that the horizontal meridian (blue activation) and vertical meridian (V1/V2 border—red activation) are clearly visible.

Supplemental Figure 7:

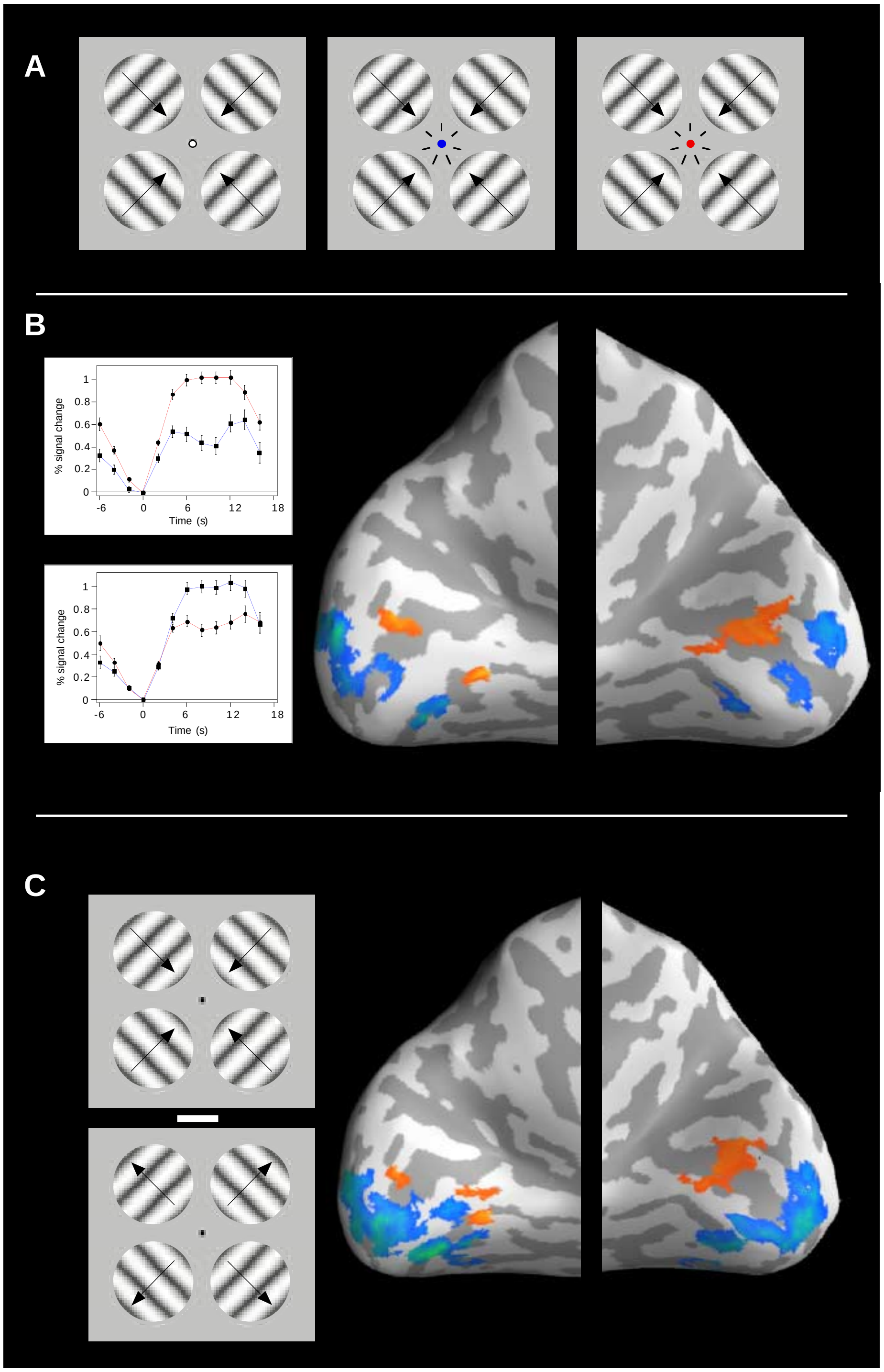

Figure 7S
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Fig. S7. An fMRI experiment to control for spatially localized attention. **A**. Throughout the experiment, subjects performed a difficult task at the fixation point. During each 10 s trial, the center of the fixation point briefly flashed blue (middle panel) or red (right panel) several times. The total number of red and blue flashes was 9 or 10 on each trial, determined randomly, and the flashes were presented at ~1 Hz (167 ms duration). Subjects were instructed to keep track of how many red and blue flashes were presented during the course of each trial and then report whether there were more red or blue flashes. Because the task occurred continuously, subjects were required to attend to the fixation point throughout each trial. Stimuli in this experiment were identical to those in Fig. S6.A—the patterns containing motion had a hard aperture. The sharp edge eliminates the illusory position shift of the patterns, which could, conceivably, help subjects identify the direction of motion while they performed the attentionally demanding task. To reduce the possibility of such an influence, we presented patterns with hard apertures. **B**. Representative results for one subject. The pattern of activation was identical to that in the first experiment: the patterns containing inward motion produced peak activation that was more peripheral, closer to the trailing edge of the motion. We found that the pattern of activation produced in this experiment was at least as strong as in the first experiment (and the experiment described in Fig. S6.A). This rules out the possibility that the results are attentionally modulated. That is, one might argue that the original results are due to attention, and that our attentionally demanding task simply did not absorb all attentional resources. However, one would still expect the strength of the activation shown in (B) to vary with attentional resources, if the effect were indeed due to attention. The fact that the pattern of activation was just as strong, if not stronger, when attentional resources were limited, indicates that the results were not a product of attention.

Supplemental Figure 8:

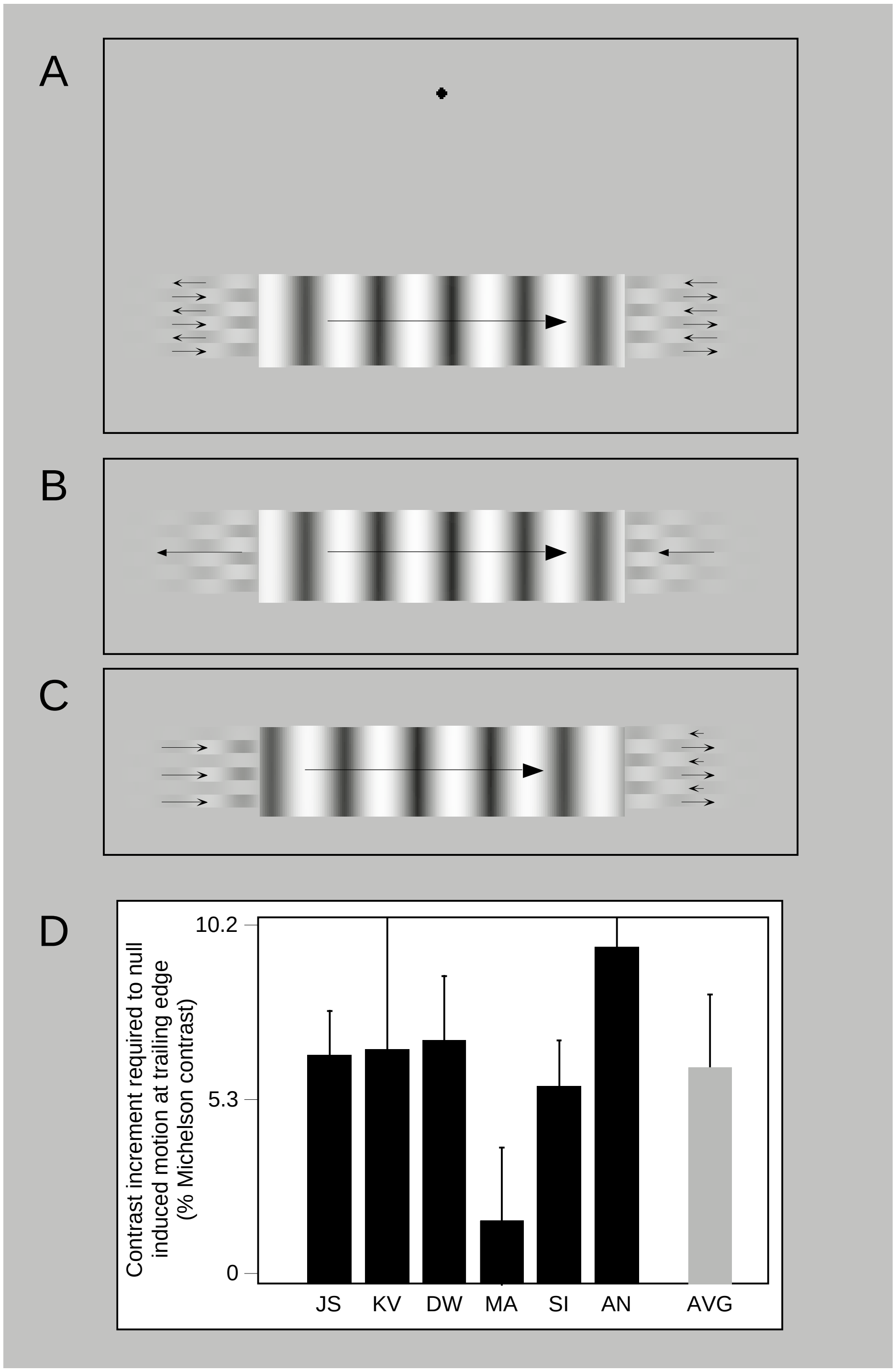

Figure 8S
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Fig. S8. Induced motion perceived in regions surrounding a pattern containing motion. **A**. When a flickering stimulus that contains no net motion signal surrounds a moving grating, the flickering pattern can appear to move in a direction opposite that of the coherently moving grating (**B**). This is a form of induced motion or motion contrast(*15-24*). In an experiment, we measured the magnitude of this induced motion at the trailing and leading edges of a coherently moving pattern. Subjects fixated on the bull's-eye shown in (**A**) while a central pattern contained either leftward or rightward motion. There were two surrounding flickering patches located on each end of the central grating (at the trailing and leading edges). Each patch consisted of a series of interleaved gratings that moved in opposite directions (as in **A**). When the contrast of the interleaved gratings moving leftward and rightward was balanced (physically equal, no net motion direction), observers perceived induced motion—the flickering stimulus appeared to contain motion in a direction opposite that of the central grating (**B**). We were interested in whether the induced motion was different at the trailing and leading edges of the coherently moving pattern. To measure the magnitude of the induced motion, we systematically altered the relative contrast between the leftward and rightward moving interleaved gratings. For example, if the central pattern contained rightward motion (**A**), the adjacent flickering stimuli appeared to move leftward (**B**); to null this illusory leftward motion, the contrast of the interleaved gratings that moved *rightward* had to be increased. Interestingly, to null the leftward induced motion that occurs at the trailing and leading edges, the contrast of the rightward interleaved gratings had to be increased more at the trailing edge than the leading edge. That is, for the surrounding flickering pattern to appear stationary, the contrast of the rightward moving elements at the trailing edge had to be higher than those at the leading edge (**C**). (See Methods for more details) **D**. The incremental Michelson contrast required to null the stronger induced motion that occurs at the trailing edge. Positive values along the ordinate show what is schematically represented in (**C**): induced motion was stronger at the trailing edge compared to the leading edge for six observers ($t_{(5)}$, $P < 0.01$).

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