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Spatial interactions in perceived speed

Hideko F Norman, J Farley Norman
Department of Psychology, Western Kentucky University, Bowling Green, KY 42101, USA
James T Todd, Delwin T Lindsey
Department of Psychology, Ohio State University, Columbus, OH 43210, USA
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Abstract. Previous research has shown that the perception of motion within a local region is influenced by other motions within neighboring areas (eg induced motion). Here, a study is reported of the perceived speed of dots moving within a circular target region, which was surrounded by other motions within a larger surrounding area. The perceived speed of the central dots was found to be fastest when the surround was stationary; it became slower as the speed of motion in the surround was increased. This decrease in the perceived target speed with increases in surround velocity occurred regardless of whether the direction in which the surround moved was the same as or opposite to the motion of the target region. This result cannot be explained by using simple models of perceived speed that depend only upon such factors as the magnitude of relative motion between center and surround. The spatial area over which these motion interactions occur was also investigated.

1 Introduction

The perception of motion within a local region is known to be influenced by other motions within neighboring spatial regions. Induced motion is one of the most prominent examples of such phenomena (Bassili and Farber 1977; Brosgole 1968; Day 1978; Duncker 1929; Gogel 1978; Reinhardt-Rutland 1988; Schulman 1981; Wallach 1959). For example, Duncker (1929) reported that a luminous spot cast by a beam of sunlight onto a rectangular piece of cardboard appeared to move in an opposite direction when the rectangle was moved back and forth. The moving rectangular framework caused the physically stationary spot to appear as if it was in motion. However, moving the spot of light did not lead to any perceptible movement of the surrounding rectangle. The Gestalt psychologists explained these phenomena using a principle involving phenomenal frames of reference (Duncker 1929; Koffka 1963).

Induced motion and other related phenomena might be explained by center–surround motion-contrast models (Murakami and Shimojo 1993; Reinhardt-Rutland 1988). Nakayama and Loomis (1974) developed a motion-contrast model based upon the output of velocity-sensitive neurons. This basic model has been supported by many subsequent neurophysiological findings in monkey cortical areas MT (Allman et al 1985; Born and Tootell 1992; Lagae et al 1989) and MST (Tanaka et al 1986). Neurons responding to motion contrast have also been found in nonprimates (Frost and Nakayama 1983). The perception of induced motion is consistent with the operation of motion-contrast mechanisms like those studied by Frost and Nakayama. For example, if motion occurs within the surround, but not the center of the receptive field of a unit (similar to the motions studied by Duncker), then they will be activated. The outputs of these motion-contrast units are ambiguous with respect to the absolute direction of motion of center and surround—ie they only signal the presence of relative motions. If perceived motion is governed by such mechanisms, then, if a unit is stimulated, some of the total relative motion it measures may be attributed to the center, and one might therefore perceive a central, physically stationary region as moving in a direction opposite to that of the surround.

The velocity-contrast-neuron model proposed by Nakayama and Loomis (1974) included two aspects of velocity: direction and magnitude. Loomis and Nakayama's finding (1973) that an analogue of simultaneous brightness contrast also existed for perceived speed suggests that the center–surround motion-contrast model could be applicable to the magnitude of velocity as well. Loomis and Nakayama showed two separated targets moving horizontally (with physically identical speed) against a field of background dots. This background had a gradient of velocities, which increased smoothly from left to right. Under these circumstances, the two targets appeared to be moving at different speeds. In particular, the target which was surrounded by slower dots appeared to be moving faster than the target which was surrounded by faster dots. Similar contrast effects involving perceived speed have been reported by Walker and Powell (1974).

Tynan and Sekuler (1975) investigated the perceived speed of dots moving inside a small centrally located target region. This target was embedded within a larger surround, which also contained moving dots. Their observers were asked to make verbal estimates of the speed of the motion of the target, which could be in a direction either the same as or opposite to that of the surround. Tynan and Sekuler found evidence of velocity tuning when the center and surround moved in the same direction. The perceived speed of the target region was slowest when the surrounding dots moved at the same physical speed, reflecting inhibition of similarly tuned units. When the center and surround moved in opposite directions, they found no evidence of tuning—increases in the surrounding velocity led to linear increments in the perceived speed of the central target area. Tynan and Sekuler suggested that their results were primarily due to inhibitory interactions between velocity-tuned neurons, and not due to differences in contrast per se.

Brown (1931) similarly showed that perceived speed was not simply proportional to actual speed, but was influenced by figural properties of a stimulus. For example, consider the situation depicted in figure 1. The shape of the two rectangles is the same (ratio of width to height is 4.0), but one rectangle is physically twice as large as the other. In situations such as this one, Brown found that the velocity of moving elements (ie circles) in the larger rectangular region needed to be twice as fast as that

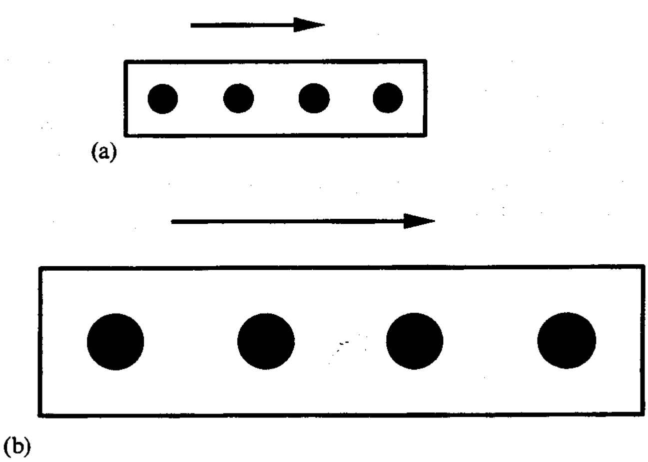

Figure 1. Schematic illustration showing two rectangular windows (a) and (b). Window (b) is twice as large as (a). Brown (1931) showed that, under these conditions, observers perceived the two speeds to be equivalent when the physical speed of (b) was twice that of (a). This phenomenon occurred even when Brown presented the two windows at the same viewing distance. When the two windows appear to have the same speeds, identical numbers of circular elements are moving through the windows per unit time.

in the smaller region for its motion to be perceived as the same speed. Under these circumstances, the same number of circular elements are moving across the large and small rectangular apertures per unit time. A related effect was more recently described by Gogel and McNulty (1983). They showed that perceived speed was affected by the density of nearby reference marks. In particular, they found that the perceived speed of a constant-velocity moving target could be altered by varying the density of neighboring stationary elements. That is, the perceived speed increased as the target moved past more neighboring elements per unit time.

All of these previous investigators have shown that the perceived speed of a moving object can be significantly influenced by the presence of other objects in neighboring areas, both moving and stationary. In order to explain the various empirical results, several distinctly different models have been proposed. The results of Brown (1931) and Gogel and McNulty (1983) imply that the visual system is not sensitive to velocity per se, but rather is using heuristics involving how many elements pass through a window per unit time, or how many neighboring elements are passed per unit time. The findings of Loomis and Nakayama (1973) are most consistent with the operation of neural mechanisms that have a center/surround receptive-field organization like those found in cortex, while those of Tynan and Sekuler seem to demonstrate the existence of lateral inhibition among neurons with similar velocity tuning. A major purpose of our experiments was to determine which of these possible explanations seems most consistent with how human observers perceive speed under a wider variety of experimental conditions.

In considering the models for perceived speed that have been proposed, it is helpful to examine what predictions they would make for an identical stimulus. One reason it is difficult to reconcile the previous findings is that in each study very different stimulus patterns were used. Let us consider the predictions of each model for a moving stimulus with a center/surround organization. Assume that the center and surround can move in either the same or opposite directions, and that the two regions can move at different velocities. Let us also examine the consequences of whether a moving pattern has a visible surround or not.

Loomis and Nakayama's demonstration (1973) of a motion analogue of simultaneous brightness contrast appears to indicate that the relative velocity between a moving target and its immediate surround (motion contrast) is an important factor in the perception of speed. Given a motion display with a distinct center and surround, a motion-contrast model would predict that the perceived speed of the center should increase when the velocity of the surrounding region increases in the opposite direction from zero, decrease when the surround velocity increases in the same direction from zero, and equal the actual speed when the surround is either stationary or not present.

Gogel and McNulty (1983) suggested from their results that perceived speed was related to how many neighbors (ie reference marks) were passed by a moving stimulus element per unit time. For a concentric center/surround stimulus, a reference-mark-density model generally makes the same predictions as a motion-contrast model. For example, when there is less motion contrast between center and surround, the center dots are also moving past fewer surrounding dots per unit time. The primary difference between the predictions of a motion-contrast and a reference-mark-density model occurs for displays that have a stationary surround. The presence or absence of a stationary surround does not necessarily affect the output of a motion-contrast mechanism. However, this distinction is important for a reference-mark-density model. When a static background is present, this model would predict that the motion of a central moving area will be perceived as faster than an identical display with no immediate background, because in the first case the central moving elements are moving past many nearby reference marks while in the second case they are not.

The results of Tynan and Sekuler (1975) suggest that inhibitory interactions take place between similarly tuned velocity detectors at nearby locations. If this is true, neighboring moving regions should not influence one another, unless their velocities are approximately equal in both direction and magnitude. For center/surround motion displays, this hypothesis would predict that observers should perceive the speed of the central region correctly for most surrounding background velocities, except for those that closely resemble that of the center.

The experiments in this study were designed in an attempt to determine which of these possible explanations seems most consistent with how observers perceive the speed of a moving object when other motions are present within neighboring areas of the visual field. The specific experiments reported here represent an extension of earlier research. For example, from the demonstration provided by Loomis and Nakayama (1973); it is not clear exactly how much the speed of a moving object is affected by the velocity contrast within its immediate neighborhood. In their experiments Gogel and McNulty (1983) used only static backgrounds, and did not investigate the role of moving surrounds. In the experiments of Tynan and Sekuler (1975), the speed of the moving central region was not manipulated, and was fixed at 2.8 deg s^{-1}. It is not clear whether the inhibition they postulated is a general phenomenon that occurs for a wider range of central velocities. In the present set of experiments we have attempted to resolve these issues by investigating the perception of speed under a wider variety of experimental conditions than has been used in the past.

2 Experiment 1

2.1 *Method*

2.1.1 *Apparatus.* The experiment was controlled by a Silicon Graphics 4D/310 VGX workstation. The stimuli were displayed on a monitor measuring 1280 × 1024 pixels (34.0 cm × 27.2 cm physical screen size). The display was viewed binocularly from a distance of 114 cm. The experiment was conducted in a dark room.

2.1.2 *Stimuli.* The stimulus displays were composed of moving fields of randomly positioned dots. Antialiasing hardware was used in drawing the dots. The motion of the dots therefore looked smooth, even at very slow speeds. The effective resolution of the display was at least 0.1 pixel.

On any given trial, the observers viewed two apparent-motion sequences, presented sequentially. Observers were first presented with unidirectional motion within a circular central area, for 2.0 s (standard stimulus). Then, a second motion sequence was presented, also for 2.0 s, in which the motion could be physically faster or slower (comparison stimulus). The comparison target was presented 1.0 s after the offset of the standard. The observers' task was to respond whether the motion of the comparison stimulus appeared faster or slower than the standard. The comparison stimulus was surrounded by motion within a surrounding concentric annulus. The motion within the central area for the standard and comparison stimuli was always in the same direction for a single trial, either upward or downward. The motion of the annular region in the comparison stimulus was in a direction either the same as or opposite to that in the central region. The diameters of the standard and comparison central regions were 3 deg visual angle, while the width of the annular region of the comparison stimulus was 1.5 deg. There was no gap between the center and surround. A schematic illustration of the stimulus displays is shown in figure 2.

The speed of dots assigned to the standard stimulus was randomly varied from trial to trial with three possible values of 0.5, 1.0, or 2.0 deg s^{-1}. The direction of motion of the standard (ie either upward or downward) also varied across trials. The velocity of the dots within the surrounding annulus of the comparison stimulus could be $\frac{1}{4}$, $\frac{1}{2}$, 1,

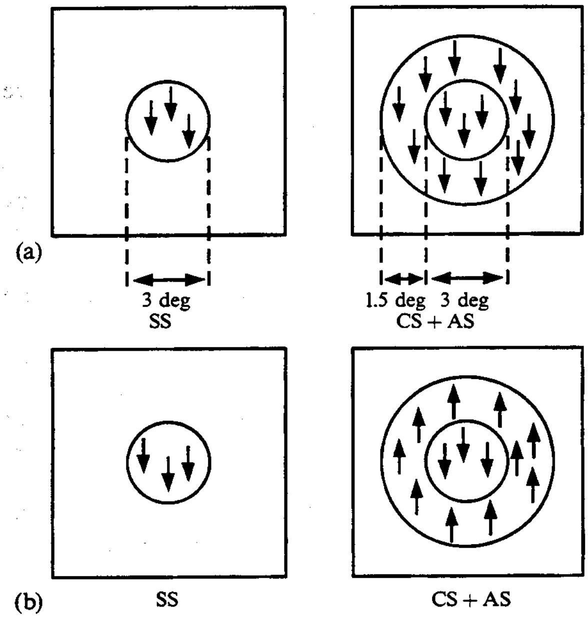

Figure 2. Schematic illustration of the two types of displays used in experiment 1. The figure shows (a) annulus motions in the same direction as the target; (b) annulus motions in the opposite direction to the target. For each display type, the left and right figures indicate, respectively, the first and second temporal intervals of a given trial. SS is the standard stimulus, CS the comparison-target stimulus, AS the annular stimulus.

2, 4, or 8 times that of the standard, in either the same or the opposite direction. An additional condition with a stationary annulus (ie zero annulus velocity) was also included. Therefore there were thirty-nine different combinations of conditions: three standard-speed conditions orthogonally combined with thirteen annulus-velocity conditions (six annulus velocities in the same direction as the target; six annulus velocities in the opposite direction to the target; one stationary-annulus condition).

2.1.3 *Procedure.* The observer's task on any given trial was to press the left mouse button if the comparison motion appeared slower than the standard. If the comparison appeared faster than the standard, the observers were instructed to press the right mouse button. The observers were instructed to fixate the center of the standard and comparison stimuli throughout the duration of each trial. We used an adaptive staircase procedure to find the speed of the comparison stimulus that looked perceptually identical to the standard. At the beginning of each staircase, for all conditions, the initial speed of the dots within the central region of the comparison stimulus was randomly assigned to be either 1/1.1, 1/1.05, 1, 1.05, or 1.1 times the standard speed. Depending upon the observer's response, the speed of the target stimulus for that staircase was either increased or decreased by a factor of 1.05 times the present speed.

The thirty-nine staircases were interleaved together in a single block of trials. Within each block, there were ten trials for each of the thirty-nine experimental conditions, which were presented in random order. Each observer participated in three experimental sessions, each containing a single block. Therefore, at the completion of the experiment, there were a total of thirty trials for each condition. We calculated the mean speed and standard deviation of the last twenty of the thirty trials for each condition. We used the mean as the estimate of the observers' point of subjective equality (PSE).

2.1.4 *Observers.* The displays were presented to four observers, all of whom were authors. All observers had normal or corrected-to-normal vision.

2.2. *Results*

The results are shown in figure 3 for each observer separately. The PSE divided by the standard-stimulus velocity is plotted as a function of the annulus velocity. If observers are able to perceive the comparison-target speed veridically, then this ratio (PSE/standard velocity) should equal 1.0. To the extent that this ratio differed from 1.0, the perceived velocity of the target area was being influenced by motions within the surrounding annular region. If the ratio is less than 1.0, this indicates that an observer perceived the comparison to be moving faster than the standard (ie they had to 'slow down' the comparison for it to appear equal to the standard). On the other hand, ratios higher than 1.0 indicate that the comparison stimulus appeared slower than the standard.

It should be evident from figure 3 that the observers' responses were greatly influenced by the motions presented within the surrounding area. All observers showed a

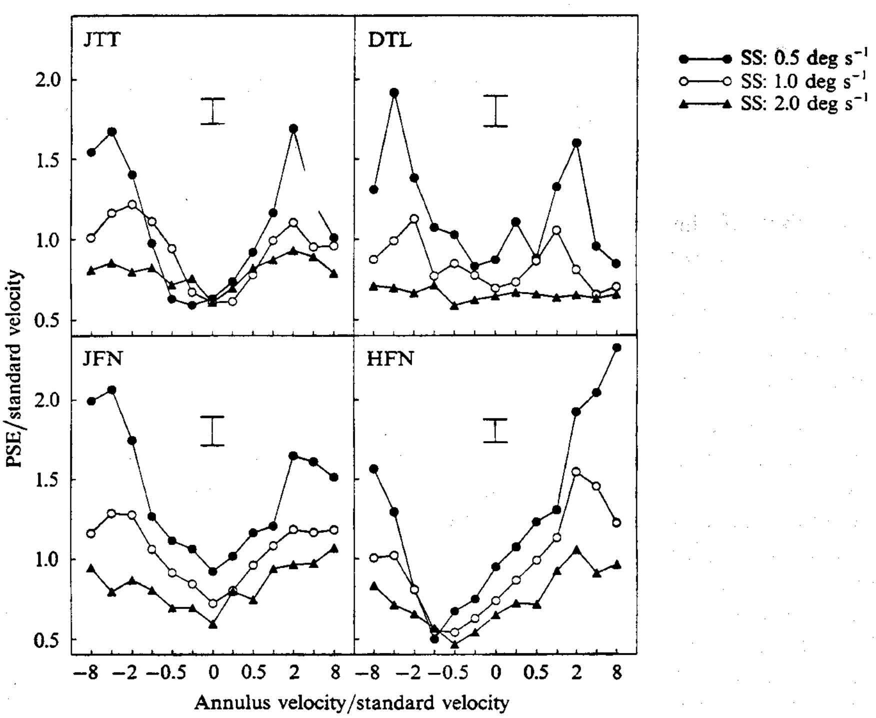

Figure 3. Results of experiment 1 for each of the four observers separately. The individual curves show the results for the three different standard-stimulus speeds (SS). The point of subjective equality (PSE) divided by the standard velocity is plotted as a function of the thirteen different annulus speeds, six speeds in the same direction as the target (positive), and six speeds in the opposite direction to the target (negative), and one stationary annulus (zero). The annulus speeds on the abscissa are plotted relative to the standard velocity so that the results for the three different magnitudes of standard speed (0.5, 1.0, 2.0 deg s^{-1}) could be compared directly. The variability of the observers' responses for a single condition is expressed as the standard deviation of the target speeds for the final twenty trials in each staircase divided by the standard velocity. A single error bar is shown for each observer and represents the average of the normalized standard deviations for all thirty-nine experimental conditions.

similar pattern of results. The functions were basically U-shaped, with the comparison appearing fastest at slow or stationary annulus velocities. As the speed of the annulus was increased, in either the same or the opposite direction, the comparison appeared increasingly slower. This modulation of apparent comparison speed by annulus velocity was greatest for the slowest standard velocities. That is, the slopes of the U-shaped functions became shallower as the standard velocity was increased. The perceived 'slowing' of the target with increasing background velocities in the opposite direction was unexpected. It is important to keep in mind that under these conditions the amount of relative motion between center and surround was increasing, but the target appeared to all observers as slowing down.

It is interesting that stationary nonmoving backgrounds had such large effects upon perceived speed. All observers' PSE/standard-velocity ratios were less than 1.0, and were lower for the higher standard-velocity conditions. We are sure that this phenomenon is a real one. In preliminary pilot observation in which comparison stimuli with no background were used, observers' PSE/standard-velocity ratios were near 1.0 with standard deviations of about 5%. Simply presenting the comparison stimuli against a stationary visible background caused their motion to appear faster.

3 Experiment 2

In the previous experiment the motions of the comparison stimulus were directly adjacent to the motions of the surrounding background points. The presence of these moving and stationary surrounds had a large impact on the perceived speed of the comparison. The purpose of experiment 2 was to determine the spatial area of the visual field over which motion in one region can influence the perceived speed of another.

3.1 *Method*

The apparatus, basic procedures, and task used in this experiment were the same as those of experiment 1. In this experiment we varied the size of a gap which separated the center and surrounding region (see figure 4). The width of the gap was either 0.0 (ie no gap), 1.5, or 3.0 deg. Three different annulus velocities were used: zero (stationary), twice as fast as the standard in the same direction, and four times faster in the opposite direction. These +2.0, and −4.0 values were chosen because they represent the velocity ratios in experiment 1 for which the perceived speeds were slowest and where perceived speed was least veridical. The three standard velocities were the same as in experiment 1. Three of the authors (HFN, JFN, and JTT) served as observers.

3.2 *Results and discussion*

Figure 5 shows the results of the three different gap conditions at each of the three different standard velocities. Each data point represents the average of the three observers' individual PSE/standard-velocity ratios. In experiment 1 we found that the perceived speed of motion within one region was strongly influenced by other motions within neighboring areas. If such interactions are dependent on spatial proximity, then they should decrease in magnitude as the separation between the regions increases. In particular, the PSE/standard-velocity ratios should become closer to 1.0 as the width of the gap is enlarged.

The basic pattern of results in the no-gap conditions was essentially identical to that of experiment 1. First U-shaped functions were again obtained, such that the perceived speed of the target region became slower at nonzero annulus velocities in a direction either the same as or opposite to the target. This phenomenon was again largest for the slowest standard velocities and was least evident at the highest standard velocities.

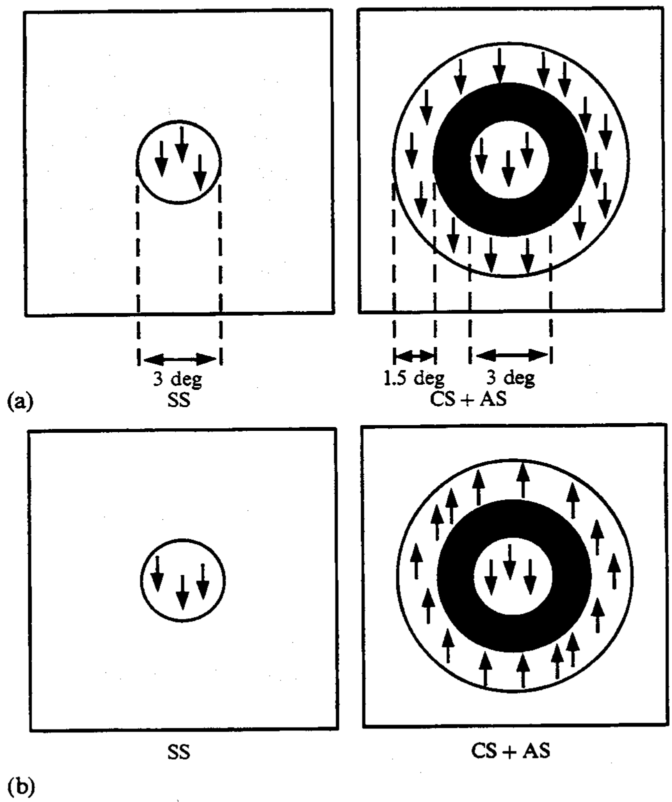

Figure 4. Schematic illustration of the two types of displays used in experiment 2. In this experiment, a gap separating the target and annular surrounding regions was introduced for both the same and the opposite annulus directions of motion. Gap sizes of 1.5 and 3.0 deg were used as well as a no-gap condition similar to that of experiment 1. Annulus and target motions in (a) the same and (b) opposite directions; left and right figures indicate, respectively, first and second interval. SS standard stimulus; CS comparison-target stimulus; AS annular stimulus.

The size of the gap separating the target and background regions had large effects. In order to confirm these effects, we conducted three nonparametric sign tests, one for each pairwise comparison of the three gap sizes. For each experimental condition, the difference between the observed PSE/standard-velocity ratio and 1.0 indicates the magnitude of the influence that the background has upon the perceived speed of the target. This difference (absolute-error magnitude) should decrease as the gap size is increased if the spatial extent of the interaction is limited. In this experiment there were nine different conditions (three annulus velocities × three standard velocities) for each gap size. Since three observers participated in the experiment, we obtained a total of twenty-seven difference values for each gap size. In twenty-two out of twenty-seven possible comparisons, the magnitude of the error differences for the no-gap conditions was larger than those for the conditions with the widest gap. The probability of this result occurring by chance alone is less than 0.001, as assessed by a one-tailed sign test. Significant differences also existed between the no gap and 1.5 deg gap conditions (twenty out of twenty-seven, $p < 0.01$) and between the 1.5 and 3.0 deg gap conditions (nineteen out of twenty-seven, $p < 0.03$). This main effect of gap size is shown in figure 6, where the average absolute-error differences are plotted for each observer. The average absolute errors decreased by 37%, 41%, and 52%, respectively, for observers HFN, JTT, and JFN as the gap width was increased from zero to 3.0 deg.

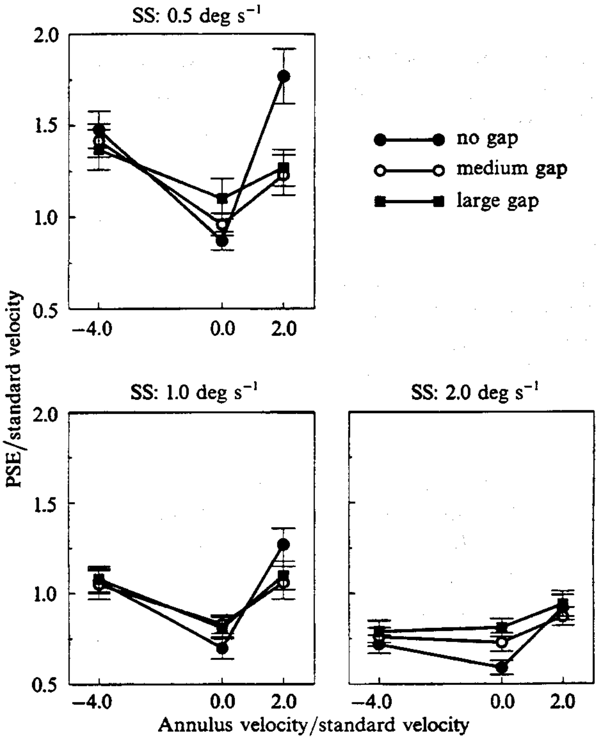

Figure 5. The results of experiment 2 for each combination of gap size and standard speed (SS), combined across all observers. The error bars indicate the mean of the three observers' normalized standard deviations. The ordinate and abscissa are as in figure 3.

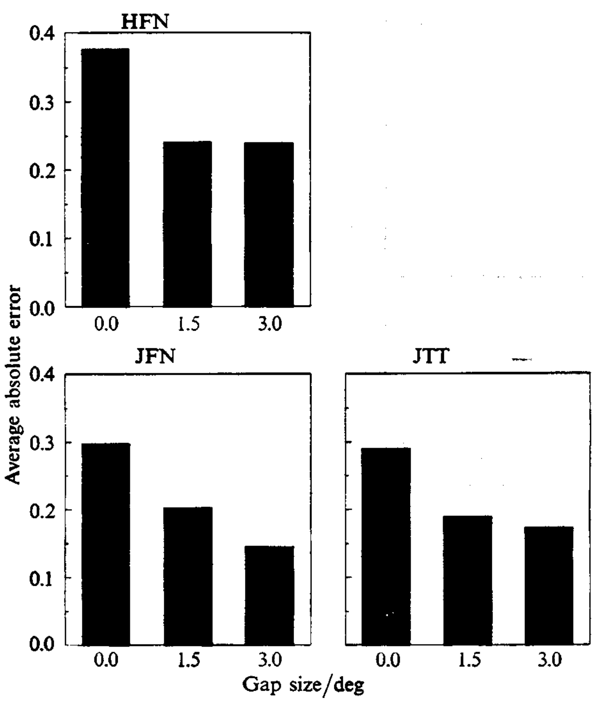

Figure 6. Results of experiment 2 plotted separately for each observer, showing the main effect of gap size, collapsed over the three different standard speeds. The average absolute error plotted on the ordinate shows the average difference between each observer's obtained PSE/standard-velocity ratios and 1.0. This measure reflects the observers' average error from veridical performance.

4 Experiment 3

The purpose of this and the following two experiments was to extend the design of the earlier experiments in order to control more carefully for any possible effects of adaptation of neural speed mechanisms. In experiment 1, there were six possible standard velocities mixed together within any given block of trials (three standard speeds × two standard directions of motion). Given the random temporal selection of one of these six values on every trial, it is unlikely that any particularly tuned velocity detector would be repeatedly stimulated over relatively short periods of time. Therefore, significant adaptation probably did not occur. The present experiment was designed to further increase the variability of the standard and test velocities to verify that the pattern of results obtained in experiments 1 and 2 were not affected by significant amounts of adaptation of neural velocity detectors.

4.1 *Method*

The number of the motion directions was increased to four (upward, downward, rightward, and leftward) in the present experiment. In addition, we randomized the presentation order of the standard-stimulus and the comparison-stimulus patterns. Therefore, the observers' task was now to judge which interval appeared faster, the first or the second. In the previous experiments, each stimulus started to move immediately at the beginning of each temporal interval within a trial. The standard and comparison stimuli in the current experiment were presented for 500 ms before the onset of movement. Otherwise, all the details of the methods and procedures were the same as those of experiment 1. The three observers were the same as those who had participated in experiment 2.

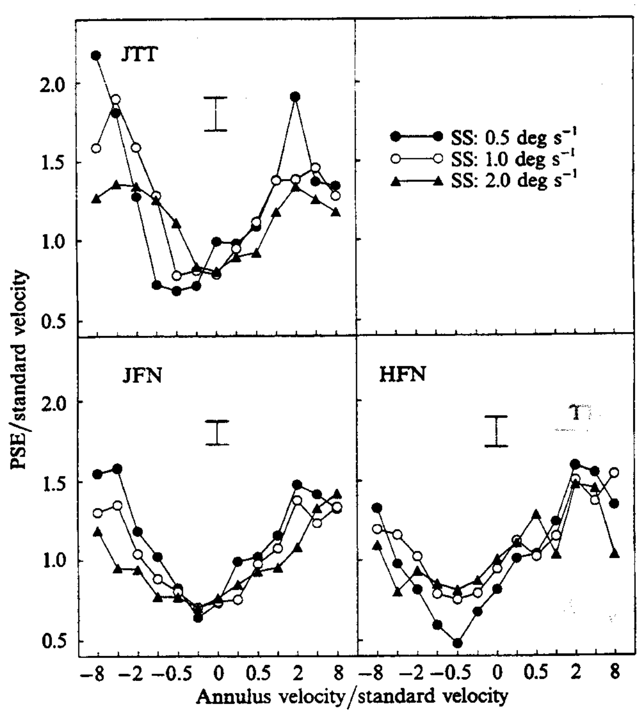

Figure 7. Results of experiment 3 for each of the three observers separately. The individual curves show the results for the three different standard-stimulus speeds (SS). The axes and error bars are as in figure 3.

4.2 *Results*
Figure 7 shows the results for all three observers separately. U-shaped functions were again obtained, similar to those of the previous experiments. The slopes of the functions became shallower as the standard velocity was increased. This trend was consistent with the results of experiment 1. In fact, the U-shape of the observers' functions is more clearly evident for the fastest standard speeds than in the analogous results of experiment 1 (see figure 3). It would appear that the basic 'slowing' phenomenon found with increasing annulus speeds in both the same and the opposite directions is robust, and is probably not due to the specific methodology employed in experiment 1. However, it should be noted that there are some quantitative differences between the results of the two experiments.

5 Experiment 4
In the previous experiments, the standard stimulus was presented without any visible background, while the comparison stimulus was surrounded by an annular region of dots. Therefore, the effects of the presence of an annulus around the comparison target cannot be entirely separated from the effects of the motions within the surrounding area. The purpose of this experiment was to determine whether the U-shaped functions are indeed a motion-related phenomenon and are due to the differences in motion between the dots in the target and those in the surround. This was accomplished by adding a stationary annular region of dots around the standard stimulus. In experiments 1, 2, and 3, a static background around the comparison caused its speed to appear faster than that of the standard (ie PSE/standard-velocity ratios less than 1.0). In experiment 4, this effect should be reduced or eliminated, since the presence of the surround should exert a similar influence on both the standard and the comparison stimulus.

5.1 *Method*
All aspects of the stimulus displays for this experiment were equivalent to those of experiment 3, except for the addition of a stationary annular region of dots surrounding the standard stimulus. The design and methodology of the experiment were identical to those of experiment 3. The observers were the same as those who participated in experiment 3.

5.2 *Results*
The pattern of results was very similar to that of experiment 3. To illustrate the similarity and the difference between the results of experiments 3 and 4, we collapsed the data across the three standard-velocity conditions in each experiment, and plotted the average PSE/standard-velocity ratios on the same graph. Each filled circle in figure 8 represents the average of the PSE/standard-velocity ratios of the three standard velocities shown in figure 7. The open circles indicate the analogous conditions in experiment 4. The two curves in figure 8 for each observer are very similar. It appears that the effect of the stationary annulus around the standard was to shift the U-shaped curves upward uniformly. The minimum of the U-shaped curves was near a PSE/standard-velocity ratio of 1.0 for all observers in the present experiment.

6 Experiment 5
Experiments 3 and 4 were designed to investigate the effects of a visible surround on the perception of the speed of a central target area in greater detail than experiment 1. In particular, an increased number of standard directions of motion were used to decrease the probability that there were any systematic effects of adaptation of neural speed mechanisms. The purpose of this final experiment was to further decrease the likelihood of significant adaptation by reducing the duration of the standard and comparison temporal intervals of each trial.

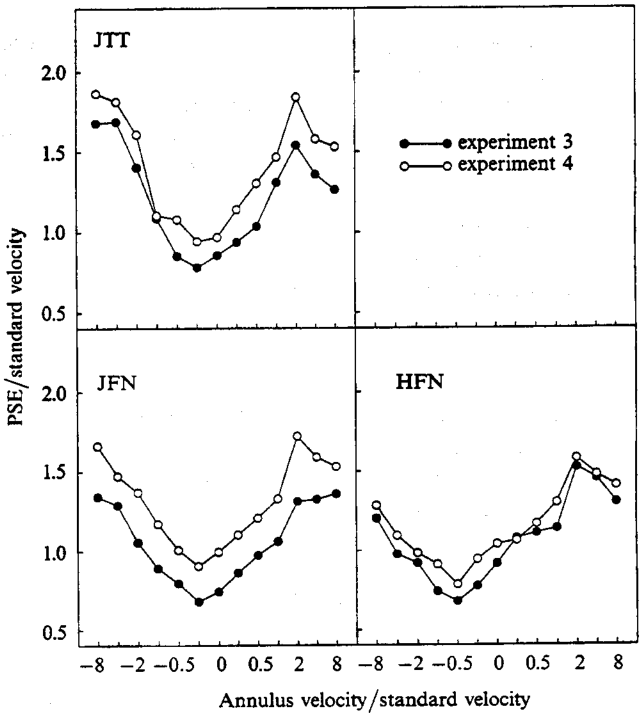

Figure 8. Results of experiment 4 for each of the three observers separately, collapsed across the three different standard-stimulus speeds. The open circles represent the results of experiment 4, and the filled circles indicate the performance of the same observers for experiment 3.

6.1 *Method*

All aspects of the stimulus displays for this experiment were equivalent to those of experiment 4, except that the duration of the motion present within the standard and comparison temporal intervals of each trial was reduced to 300 ms. The design and methodology of the experiment were identical to those of experiment 4. The observers were the same as those who participated in the three earlier experiments.

6.2 *Results*

The results of this experiment are shown in figure 9. The basic pattern of results was identical to those of the earlier experiments. Therefore, we combined the data from the three standard velocity conditions in order to highlight the similarities between the results of this experiment (open circles) and those of experiment 4 (filled circles). All of the observers reported that the task was subjectively more difficult with brief motion presentations. However, this did not seem to affect the qualitative pattern of the results in any systematic way. The similarity of the results across all of the experiments suggests that the influence of moving backgrounds on the perceived speed of a central region are a genuine effect involving interactions between mechanisms devoted to the analysis of motion at different regions of the visual field, and are not due to any differential effects of adaptation across mechanisms tuned to different magnitudes of velocity.

7 General discussion

The results of the present experiments have shown that the perceived speed of a moving region is greatly influenced by the presence of other motions within neighboring areas. In particular, we found that as the magnitude of the speed of a surrounding

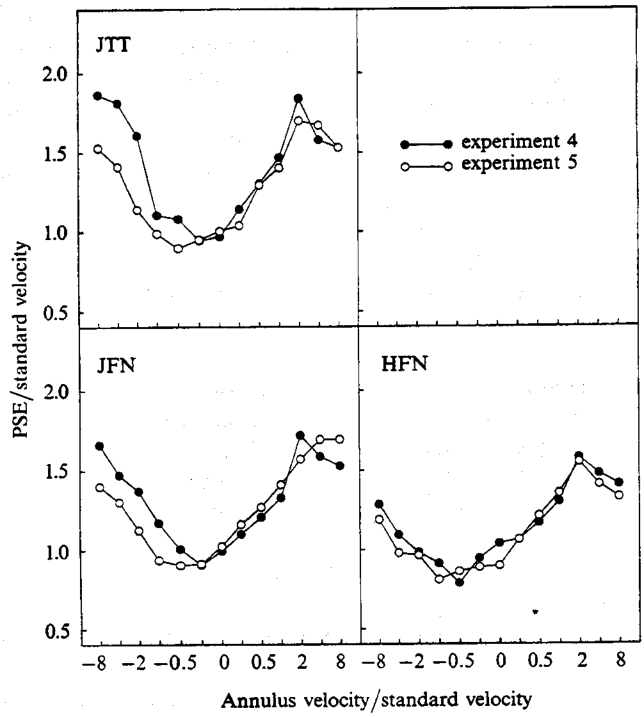

Figure 9. Results of experiment 5 for each of the three observers separately, collapsed across the three different standard-stimulus speeds. The open circles represent the results of experiment 5, while the filled circles indicate the results of the same observers for experiment 4.

annulus was increased, the apparent speed of a central moving target decreased by a significant amount. This reduction in perceived speed occurred both when the surround moved in the same direction as the target and when it moved in a direction opposite to that of the target. When a gap was introduced between the center and surround, the magnitude of the distortions in perceived speed decreased, indicating that the spatial area over which motion interactions occur is limited. The apparent speed of a moving stimulus was also affected by nonmoving (static) backgrounds. In particular, when a target was surrounded by a stationary annulus, its motion appeared faster than that of an identical standard region that did not have a surround.

Several aspects of our results can be explained by existing models of perceived speed. For example, we found that the apparent speed of a target decreased as the speed of a surrounding annulus was increased in the same direction from zero, which could be due to a reduction in motion contrast. However, the magnitude of motion contrast cannot explain the perceived slowing of the target in opposite-direction conditions. For example, as the annulus speed increased in the opposite direction, the amount of motion contrast increased, but the perceived speed of the target *decreased* for all observers. This perceived slowing for both the same and the opposite directions of annulus motion created the characteristic U-shaped functions shown in figures 3, 7, 8, and 9. One possibility that is consistent with these results is that the velocities of both the center and the surround were subjected to a full-wave rectification prior to a calculation of motion contrast. One way in which this rectification might occur is if the velocity detectors that feed into a motion-contrast mechanism were themselves insensitive to direction of motion.

Several investigators have found evidence that appears to support this hypothesis (Smith 1985; Smith and Edgar 1994; Thompson 1981; Watson et al 1980). For example, Smith (1985) used an adaptation paradigm to investigate perceived speed, and found that adaptation to a moving pattern caused the motion of a subsequently presented stimulus to appear slower than its actual speed. This apparent slowing of the test stimulus occurred when the adapting stimulus moved in the same direction as the test. It also often occurred when the adapting stimulus moved in the opposite direction. To explain the opposite-direction results, Smith and Edgar (1994) proposed a model of perceived speed in which one of the important component mechanisms is not tuned for direction of motion. If the calculation of motion contrast between center and surround was based upon velocity detectors that had a similar insensitivity to direction of motion, one might obtain a U-shaped pattern of results like those found in the present experiments.

The model of Tynan and Sekuler (1975) postulating interactions between velocity-tuned mechanisms makes a very specific prediction that the perceived speed of the comparison should be slowest for an annulus-velocity/standard-velocity ratio of 1.0, where nearby similarly tuned units ought to inhibit one another. The peaks in figures 3, 7, 8 and 9 indicate those conditions where the speed of the comparison stimulus appeared the slowest. The curves for all observers have clearly defined peaks, but these peaks typically occurred not at annulus-velocity/standard-velocity ratios of 1.0, but at ratios of 2.0. In addition, a strict implementation of this model would make the prediction that motion in the surround in the opposite direction would not affect the apparent speed of a target region, since interactions between velocity detectors should only occur when similarly tuned nearby units are activated. Since we did find that opposite directions of motion can significantly affect the perceived speed of a target, it would appear that a model of perceived speed that is based entirely upon the notion of inhibition between similarly tuned neurons sensitive to velocity is incomplete or inadequate to explain the perception of speed in more-general circumstances. The support for the inhibition model was based largely upon the results of Tynan and Sekuler (1975). The difference between their results and ours may be due to the choice of standard center speeds. The U-shaped functions we obtained were steepest at the lowest standard speeds (0.5 and 1.0 deg s^{-1}) and shallowest at the highest standard speed of 2.0 deg s^{-1} (see figures 3 and 7). Perhaps it is not surprising that Tynan and Sekuler did not obtain U-shaped functions similar to ours, since they used only a single, relatively fast center speed of 2.8 deg s^{-1}.

Upon first reflection, it would appear that a motion-contrast model would also predict that there should be definite peaks in the observers' results for annulus-velocity/standard-velocity ratios of 1.0. At a ratio of 1.0, the center and surround of the comparison are moving at the same speed. The amount of contrast between those two regions is zero, and one might therefore expect that the perceived speed of the comparison should be slowest for that condition. However, it is important to keep in mind that there is another motion contrast in the stimulus—the dots in the surrounding annulus are moving relative to their surround. The perceived speed of this stimulus would necessarily be some function of these two motion contrasts. Once this is taken into consideration, it is not clear that one would expect definite peaks in the observers' functions for any particular annulus-velocity/standard-velocity ratio.

One final possibility that remains to be considered as an explanation for the peaks in the observers' results is that at some point, as the annulus speed increases, the motion is too fast to be coherently detected, and consequently exerts less of a modulating influence on the perceived speed of the central region. If this hypothesis were true, then the peaks would occur at lower and lower annulus-velocity/standard-velocity ratios as the magnitude of the standard velocity is increased. The fact that this did not take place, and that the peaks in the functions always occurred for annulus-velocity/standard-velocity ratios of approximately 2.0 would seem to discount this possibility.

The finding in our experiments that the presence of a stationary background affects the perceived speed of a moving central region cannot be explained by either a motion-contrast model or by some simple modification of a motion-contrast model. The observed increase in apparent speed caused by static neighboring patterns is similar to the findings of Gogel and McNulty (1983), who found that increases in the density of a stationary row of nearby reference marks resulted in an increase in the perceived speed of a target moving at a constant velocity. A reference-mark-density model would predict that the more elements passed per unit time, the faster the apparent velocity. The results of the current experiments for stationary backgrounds and for annulus motions in the same direction as the target are consistent in many respect with such a model. However, the opposite-direction results are inconsistent.

All of our findings demonstrate that predicting the perceived speeds of moving patterns is not simple, and no single current perspective can explain all aspects of the observers' judgments. As we have seen, the perception of the speed of a moving region is affected by many factors other than the actual speed. Since many of the important features of our results can be captured by different models, it seems possible that some combination of currently known velocity mechanisms will eventually account for the diverse set of phenomena involved in the perception of speed.

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References

Allman J, Miezin F, McGuinness E, 1985 "Direction- and velocity-specific responses from beyond the classical receptive field in the middle temporal visual area (MT)" *Perception* **14** 105 – 126

Bassili J N, Farber J M, 1977 "Experiments on the locus of induced motion" *Perception & Psychophysics* **21** 157 – 161

Born R T, Tootell R B H, 1992 "Segregation of global and local motion processing in primate middle temporal visual area" *Nature* (*London*) **357** 497 – 499

Brosgole L, 1968 "An analysis of induced motion" *Acta Psychologica* **28** 1 – 44

Brown J F, 1931 "The visual perception of velocity" *Psychologische Forschung* **14** 199 – 232

Day R H, 1978 "Induced visual movement as nonveridical resolution of displacement ambiguity" *Perception & Psychophysics* **23** 205 – 209

Duncker K, 1929 "Über induzierte Bewegung (Ein Beitrag zur Theorie optisch wahrgenommener Bewegung)" *Psychologische Forschung* **12** 180 – 259

Frost B J, Nakayama K, 1983 "Single visual neurons code opposing motion independent of direction" *Science* **220** 744 – 745

Gogel W C, 1978 "The adjacency principle in visual perception" *Scientific American* **238** 126 – 139

Gogel W C, McNulty P, 1983 "Perceived velocity as a function of reference mark density" *Scandinavian Journal of Psychology* **24** 257 – 265

Koffka K, 1963 *Principles of Gestalt Psychology* (New York: Harcourt, Brace and World)

Lagae L, Gulyas B, Raiguel S, Orban G A, 1989 "Laminar analysis of motion information processing in macaque V5" *Brain Research* **496** 361 – 367

Loomis J M, Nakayama K, 1973 "A velocity analogue of brightness contrast" *Perception* **2** 425 – 428

Murakami I, Shimojo S, 1993 "Motion capture changes to induced motion at higher luminance contrasts, smaller eccentricities, and larger inducer sizes" *Vision Research* **33** 2091 – 2107

Nakayama K, Loomis J M, 1974 "Optical velocity patterns, velocity-sensitive neurons, and space perception: a hypothesis" *Perception* **3** 63 – 80

Reinhardt-Rutland A H, 1988 "Induced movement in the visual modality: An overview" *Psychological Bulletin* **103** 57 – 71

Schulman P H, 1981 "Antagonistic effects of adjacency and apparent speed in induced movement" *Journal of Experimental Psychology: Human Perception and Performance* **7** 985 – 994

Smith A T, 1985 "Velocity coding: evidence from perceived velocity shifts" *Vision Research* **25** 1969 – 1976

Smith A T, Edgar G K, 1994 "Antagonistic comparison of temporal frequency filter outputs as a basis for speed perception" *Vision Research* **34** 253 – 265

Tanaka K, Hikosaka K, Saito H, Yukie M, Fukada Y, Iwai E, 1986 "Analysis of local and wide-field movements in the superior temporal visual areas of the macaque monkey" *Journal of Neuroscience* **6** 134–144

Thompson P, 1981 "Velocity after-effects: The effects of adaptation to moving stimuli on the perception of subsequently seen moving stimuli' *Vision Research* **21** 337–345

Tynan P, Sekuler R, 1975 "Simultaneous motion contrast: velocity, sensitivity and depth response" *Vision Research* **15** 1231–1238

Walker P, Powell D J, 1974 "Lateral interaction between neural channels sensitive to velocity in the human visual system" *Nature (London)* **252** 732–733

Wallach H, 1959 "The perception of motion" *Scientific American* **201** 56–60

Watson A B, Thompson P G, Murphy B J, Nachmias J, 1980 "Summation and discrimination of gratings moving in opposite directions" *Vision Research* **20** 341–347