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Motion grouping impairs speed discrimination

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Abstract

Discriminating between two speed signals is harder when they are seen as part of a single trajectory, compared to the case when they appear as distinct entities. Observers were asked to judge which half of a display had dots that were moving faster. This was done under two main conditions: when dot motion appeared to continue across the boundary between the two halves, and when it moved parallel to the boundary. Speed discrimination thresholds were elevated when motion in the two halves appeared to cross the boundary compared to the case when motion was parallel to the boundary. Extensive practice improved performance until speed discrimination in the two cases was virtually indistinguishable. The addition of noise caused the original effect to reappear, i.e., thresholds were elevated when motion continued across the border. Our results suggest that the local differences in velocity on either side of border are ignored when motion appears to cross the border. Instead the visual system seems to enforce an a priori assumption that when motion continues across a boundary it belongs to a common motion path.

Keywords: Motion trajectory; Speed discrimination; Prior visual experience; Segmentation; Acceleration

1. Introduction

Numerous studies have shown that human observers are not very sensitive to visual acceleration. In fact, Weber fractions for detecting a change in the ongoing velocity of a moving target are typically between 0.15 and 0.3, values that are several times higher than speed discrimination for spatially or temporally segregated stimuli (Bravo & Watamaniuk, 1995; Gottsdanker, 1956; Snowden & Braddick, 1991; Watamaniuk & Duchon, 1992). To explain the human inability to detect acceleration, Nakayama (1985) suggested that velocity signals were integrated for a substantial duration after their initial encoding. This second-stage integrator would smooth the velocity field and reduce noise. Alternatively, velocity signals that are seen as part of the same surface or as following a common trajectory may be grouped together in a way that obscures local velocity perturbations. For example, Verghese and Stone (1995, 1996) found that speed discrimination was worse for a single large patch than for multiple small patches, even though the total stimulus area was the same in the two cases. This finding suggests that bringing motion elements into close proximity impairs speed discrimination. From their work on the detection of trajectories in noise, Watamaniuk, McKee, and Grzywacz (1995) suggested that similar motion signals are grouped along a smooth motion path. More recent work has shown that motion signals are not strictly combined, but that the initial motion segment cues subsequent motion in the vicinity (Verghese & McKee, 2002). Are these integration or grouping processes obligatory or do they instead reflect expectations about naturally occurring motions?

Objects in motion rarely change direction and speed abruptly. Based on past visual experience, we expect objects in motion to continue along their trajectories without abrupt changes in speed (Weiss, Simnocelli, & Adelson, 2002). Thus, the visual system may treat local

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velocity changes as noise to be ignored, even if detected. If so, this 'prior' for smooth velocity could be overridden by experience or training that made the acceleration task-relevant. In this study, we examine how the spatial layout of velocity signals affects the ability to discriminate velocity differences. We shall also explore the role of practice in detecting velocity changes.

Consider the case when an observer has to discriminate the speed of moving dots in two halves of a circular display. In Fig. 1A, the dots move parallel to the boundary, while in Fig. 1B they move orthogonal to the boundary such that the dots appear to continue across the boundary. Our prediction is simple. If perception is influenced by prior experience with objects in motion that do not change speed or direction abruptly, then speed differences will be harder to discriminate in the case when motion crosses the boundary than when motion is parallel to the boundary.

Our experimental design is well suited to examining both segmentation effects due to motion parallax and integration effects that are thought to interfere with the detection of acceleration. With a 90° rotation of motion direction with respect to the boundary, we can go from the parallel condition that favors segmentation due to motion parallax (Mestre, Masson, & Stone, 2001) to the orthogonal condition that appears to favor integration. This latter condition is equivalent to the dots undergoing an acceleration or deceleration at the boundary. Several studies (Nakayama, 1985; Snowden & Braddick, 1991), have suggested that the visual system is not sensitive to detecting acceleration because local signals are integrated over time. Here, we show that while observers are initially poor at detecting speed differences in the orthogonal (acceleration) condition, they learn to access the local signals with practice. These results argue in favor of observers modifying their prior, rather than a compulsory integration process.

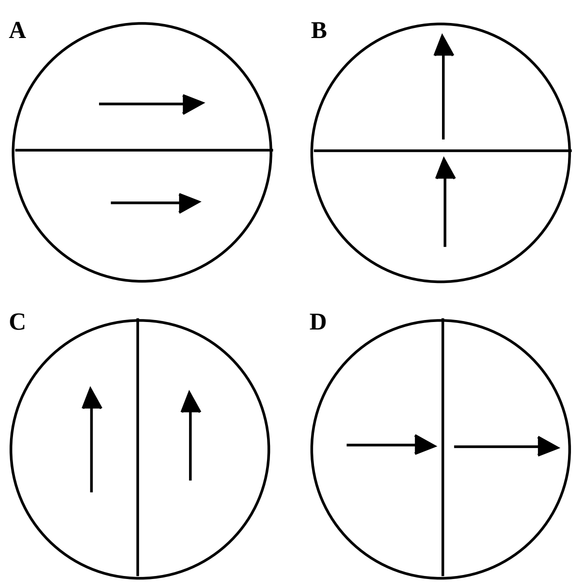

Fig. 1. The four possible stimulus configurations. (A) An invisible horizontal border divides the display into two halves and motion is horizontal, i.e., parallel to this border. The direction of motion is randomly left or right in each trial and both halves move in the same direction. (B) The border is horizontal and motion is vertical, orthogonal to the border. The motion direction is either up or down in both halves. In (C and D) the border is vertical. Motion direction is vertical and parallel to the border in (C) and horizontal and orthogonal to the border in (D).

2. Methods

We used a circular display of radius 6°. The display was split along a horizontal midline as described above. We also added conditions where it was split along a vertical midline (Figs. 1C and D). The dividing line was never physically present, although observers had full knowledge of its orientation in Experiments 1 and 2. The moving dots had different speeds on either side of this midline. Dots moved either parallel to the boundary, or orthogonal to the boundary appearing to continue across the border. In Experiment 1, the dividing line was always horizontal, which meant that dot motion was horizontal in the parallel condition and vertical in the perpendicular condition. To control for the possibility of differential sensitivity to horizontal vs. vertical motion, the dividing line in later experiments was either horizontal or vertical. Thus, the orientation of the dividing line and the parallel vs. orthogonal condition determined the direction of the dots. For a display divided along the vertical midline in these later experiments, dots moved in the vertical direction in the parallel case, and moved in the horizontal direction in the orthogonal case. The converse was true for a display divided along a horizontal midline. Each of these four conditions was run in separate blocks. In a given block with say horizontal motion parallel to a horizontal border, the dots all moved to the left or to the right, so that their motion was not predictable from trial to trial. Similarly, the dots moved randomly up or down in conditions with vertical dot motion.

The duration of the display was 200 ms, which at the 71 Hz frame rate of the monitor, corresponded to 14 frames of the stimulus. The base speed of the dots was 12°/s. When dots left the circular stimulus region, they wrapped around. One-half of the display, picked at random, was assigned the base speed, and the other half was assigned the speed increment. Observers were asked to pick the half with the faster speed. Feedback was provided. Proportion correct in this spatial two alternative forced-choice (2AFC) task was plotted as a function of speed difference.

Typically, the display contained 400 dots, divided equally between the two halves. We also performed additional experiments where half the dots in the display were substituted by noise dots in Brownian motion.

These noise dots had the same displacement between frames as the "signal" dots, but the direction of this displacement was randomly chosen for each noise dot. All the dots whether signal or noise had a contrast of 50% with respect to the background luminance of 45 cd/m^2.

Thresholds for the different motion configurations were examined in separate blocks of trials. Each block had 20 trials at each of 5 values of speed difference, with a total of a 100 trials per block. Weibull functions were fit to the data in each block and thresholds were estimated as the speed difference corresponding to 82% correct. The threshold error was estimated using a bootstrap procedure psignifit (Wichmann & Hill, 2001), that estimated the 68% confidence intervals (corresponding to ±1SD of threshold obtained over 999 simulations).

A total of four observers participated in the experiments. Two were authors and two others were naïve as to the purpose of the experiment.

3. Experiment 1: The influence of spatial layout

In this set of experiments we compared speed discrimination thresholds for cases when motion was parallel to the boundary and when it appeared to cross the boundary. The display was divided into two halves along a horizontal axis. Motion parallel to the border was horizontal; motion crossing the border was vertical or oblique. In Fig. 2, the solid bars show speed discrimination, in terms of Weber fraction (speed difference/base speed) for the different motion configurations for two observers. For the case when the two halves were contiguous and motion was parallel to the boundary, speed discrimination was easy and thresholds were low. When motion appeared to cross the boundary, thresholds were elevated almost by a factor of two. Additional experiments with oblique stimuli showed that this was true even when the motion crossed the border in an oblique direction. Both observers showed the same pattern except that observer SPM thresholds were significantly elevated for oblique motion crossing the border. In general, thresholds were elevated whenever the motion in the two halves was consistent with motion along a path. Motion parallel to the border was not required for low thresholds. We tested a condition in which motion was oblique, but the motion in the two halves differed in direction by 90°. In this case, thresholds were low, similar to those when motion was parallel to the border.

Perhaps in the case when motion appears to continue across the boundary, segregating the display into two regions might prevent the motion signals in the two halves from being combined. We did this by assigning a different polarity to the dots in each half of the display in the vertical motion case. The dots in one half of the display were lighter than the background and those in the other half were darker than the background. This manipulation

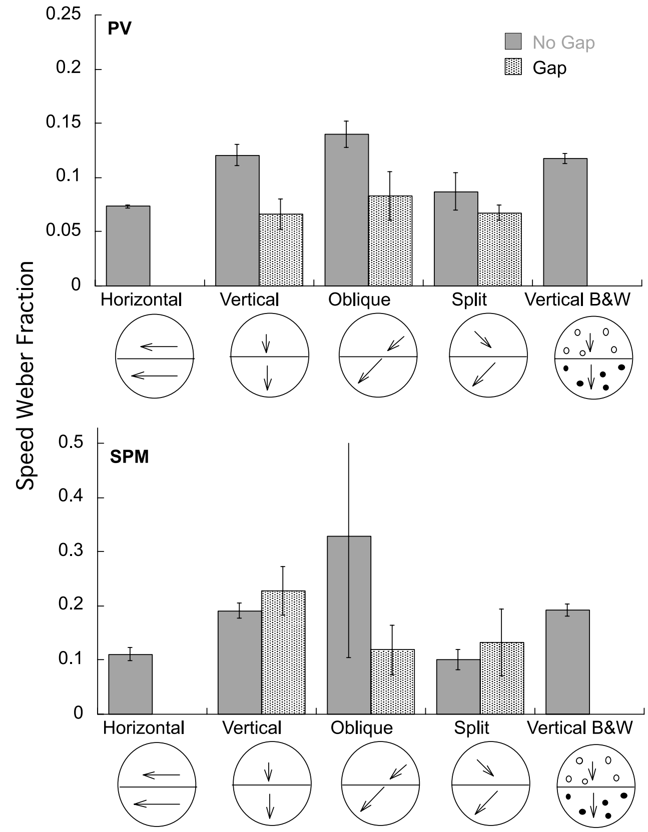

Fig. 2. Speed discrimination thresholds for configurations with a horizontal border. The five configurations show speed Weber fractions for cases when the motion direction is parallel, orthogonal, and oblique with respect to the border. For comparison, thresholds are also shown for the "split" case when motion direction is oblique to the border but changes by 90° at the border. The opposite polarity case is a variant of the orthogonal motion case where dots on one side of the border are all light, or all dark. The solid bars plot thresholds when the two halves of the display abut and the dotted bars plot thresholds when there is a 1° gap between the upper and lower halves. The error bars represent the standard deviation of the threshold estimate across repeated blocks.

seemed to have no effect. Thresholds when motion appeared to cross the border were similar when the dots in the two halves had the same-polarity, or had opposite polarity.

If the high thresholds occur because the motion in the two halves appear to be connected when the motion crosses the border, then creating a blank region might prevent the two motions from being connected. We separated the two halves by blanking out the central 1° of the display, meaning that there was a horizontal 1° wide strip at the center of the display that was devoid of dots. The stippled bars in Fig. 2 show thresholds for the gap condition. Creating a physical gap between the two halves of the display seemed to have the desired effect: thresholds in the gap condition when motion appears to cross the boundary were as low as in the case when motion is parallel to the boundary. For observer SPM, a 1° gap in the case of motion orthogonal to the border (vertical) was insufficient to bring thresholds down to the case when motion was parallel to the border. However, there is evidence that trajectory detection is unaffected by small gaps in the trajectory (Verghese, McKee, & Grzywacz, 2000; Watamaniuk & McKee, 1995), so trajectory grouping for the vertical motion may persist across this border for this observer. Note that 1° border effectively blocks more of the oblique trajectory than the vertical trajectory, which may account for the improvement obtained with the oblique trajectory for this same observer.

Our results so far show that speed discrimination is impaired when motion appears to cross the boundary. If one considers the local signals on either side of the boundary, the speed differences are as strong when the motion is orthogonal to the border as when it is parallel to the border. Our results suggest that these local speed differences are ignored when motion appears to cross the border. Instead the visual system seems to enforce a prior that assumes, when motion continues across a boundary it belongs to a common motion path. The motion is perceived to be largely uniform, and small changes in speed across the border are attributed to noise. We wondered whether the local signals were lost or could be recovered with practice.

Fig. 3 plots observer PV's thresholds for motion orthogonal and parallel to the boundary over a course of 3 months. These are data analyzed post hoc for practice effects and not part of a systematic study investigating whether local signals could be accessed. Each data point is the average of thresholds measured on a given day across two or three blocks of trials. During the middle period, we were testing a slightly different configuration so no data points are shown here. Fig. 3 shows that when motion crosses the border thresholds improved during this period, to the point where they were more or less similar to the thresholds for the case when motion is parallel to the border. These data show that thresholds improve with practice when motion crosses the border and suggests that observers learn to access the local signals on each side.

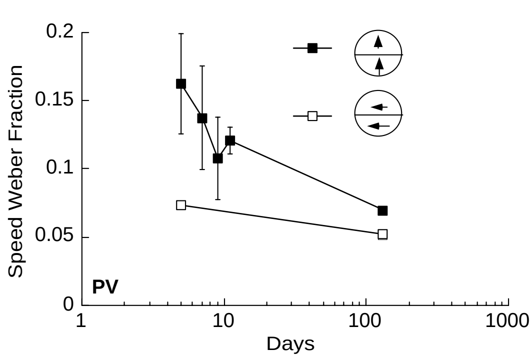

Fig. 3. Speed discrimination thresholds, analyzed post hoc, for learning effects. The filled and open squares plot thresholds when motion is orthogonal to the border, and parallel to the border, respectively. Initially thresholds are elevated for orthogonal motion, while thresholds for parallel motion are comparable with thresholds measured in other studies. With practice thresholds for orthogonal motion improve and approach the value of thresholds for parallel motion. The error bars represent the standard deviation of the threshold estimates measured on a given day. When the error bar is not visible, it is smaller than the size of the symbol.

4. Experiment 2: Effect of practice

In these experiments, we tested two practiced observers (PV and CB) on two additional novel configurations. Previously, we had compared vertical motion across a border with horizontal motion parallel to the border (first two columns of Fig. 2). In this experiment, we just rotated these configurations, so that the horizontal motion was across a border and the vertical motion was parallel to the border. To address the possibility that the difference in thresholds measured for motion orthogonal and parallel to the boundary could be due to different sensitivities to horizontal and vertical motion, we used a different set of novel conditions for our third observer. We used only vertical motion for observer NK in both the parallel and orthogonal configurations.

To demonstrate practice effects, we plot thresholds as a function of block number: recall that a block consists of 100 trials and that threshold estimates for each of these blocks is thus somewhat noisy. The first block of trials for the four conditions are shown in one group, the second in another group and so on. The solid bars are for the case when motion was orthogonal to the boundary and hashed bars are for the case when it was parallel to the boundary. Within each block the first pair of dark bars represent the new conditions, whereas the light bars represent thresholds for the older configurations measured during the same session for purposes of comparison. By the time we measured thresholds in the new conditions for observers PV and CB, thresholds for the older orthogonal and parallel configurations were comparable. The error bars represent confidence intervals estimated by a bootstrap procedure.

The most experienced observer (PV) shows no effect of practice for the novel configurations; she is equally good at both of them. Perhaps, the extensive practice with the original configurations has transferred to this novel rotated pair. Observer CB had had less experience with the original configurations, so his results for the novel configurations show solid practice effects, particularly for motion across the border. Nevertheless, the speed thresholds for motion across the border remains slightly elevated relative to parallel motion even after practice. A similar pattern is apparent for the naïve observer tested with the original configuration (see Fig. 4). This observer had no prior experience with this task. In the first block of trials, her thresholds were elevated both for motion parallel and orthogonal to the border. Thresholds rapidly

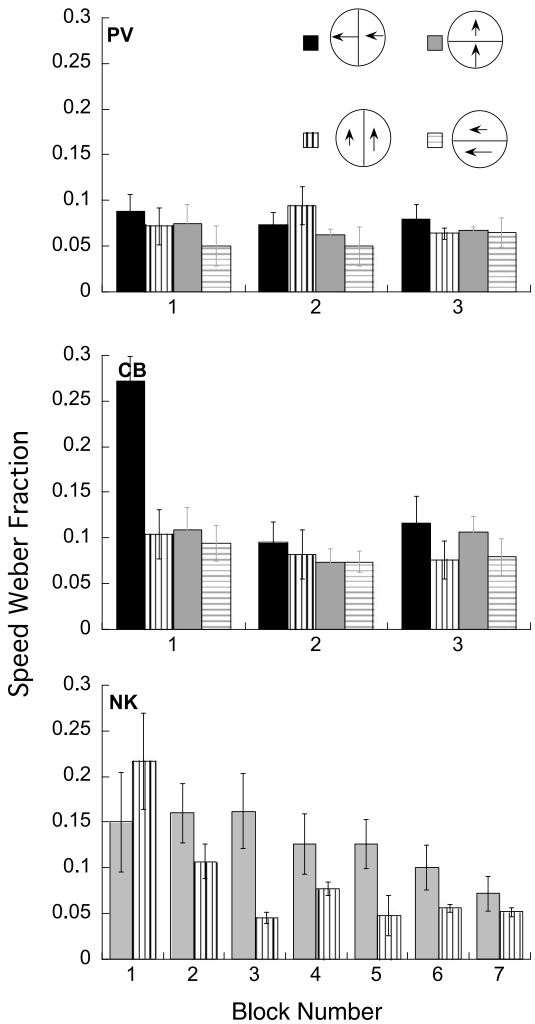

Fig. 4. Speed discrimination for new configurations. Thresholds were estimated from the 100 trials within a single block and are plotted as a function of the block number. For practiced observers PV and CB, the new configurations have an invisible vertical border (Fig. 1C and D). The data for these new configurations are shown in black, while the data for the old configuration measured around the same time are shown in gray for comparison. Observer NK, who had not prior experience with this task, was tested with only vertical stimuli.

improved for the parallel motion case and improved more slowly for the orthogonal motion case.

As can be seen, the difference in thresholds between the orthogonal and parallel motion configurations quickly diminishes with practice. Thus, it appears that with practice, observers overcome the prior of smoothing signals along the motion path and can access local signals on either side of the border even when these are consistent with motion continuing across the border.

However, observers needed to relearn the ability to use local speed signals when the original displays were modified by the presence of dynamic noise dots. In the noise condition, half the signal dots were replaced by noise dots in Brownian motion. Fig. 5 shows data for three observers, the author and two naïve observers. Thresholds are elevated for the first blocks of the

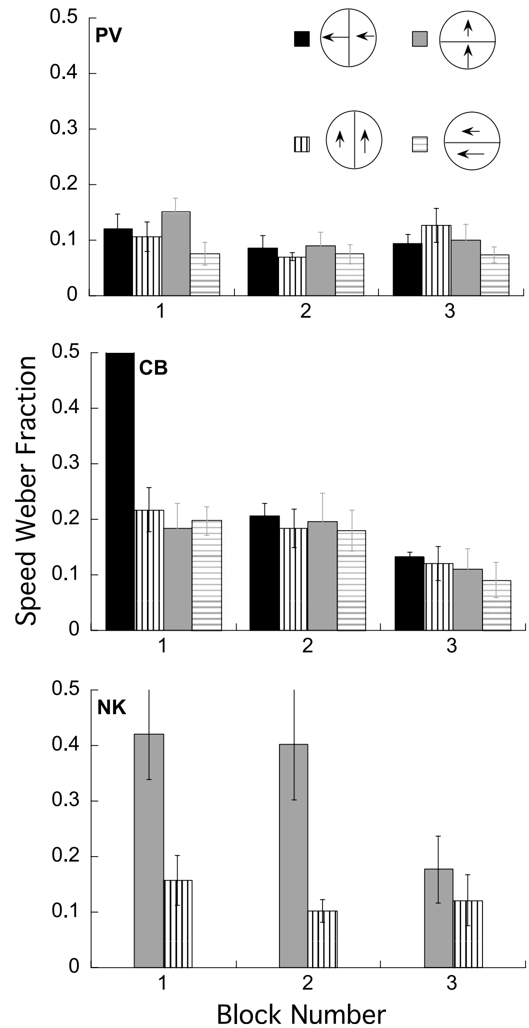

Fig. 5. Speed discrimination in the presence of noise. One-half of the dots in the display were replaced by noise dots in Brownian motion. Thresholds for all four configurations are plotted as a function of block number.

new noise condition. Observer PV shows a small effect of added noise in the first block of trials, particularly when motion is orthogonal to the boundary. Observer CK's thresholds are initially elevated for all noise conditions, but dramatically so for horizontal motion that crosses the border. The threshold for this condition is outside the scale of the graph and is 0.75 ± 0.50. Recall that the large error bars are due to the fact that thresholds are estimated from 100 trials in the block. Observer NK's thresholds are considerably elevated only when motion crosses the border. Even though the difference in thresholds in the two configurations is initially substantial, it quickly diminishes with practice.

5. Experiment 3: Shear detectors

Our results show that speed discrimination thresholds are elevated when motion crosses the border, relative to when it is parallel to the border. This is because thresholds when motion is parallel to the border are comparable with thresholds measured in other speed discrimination tasks (McKee, Silverman, & Nakayama, 1986). But it is possible that under the conditions of our display that speed discrimination is not impaired when motion crosses the border, but rather that it is aided by special cues when motion is parallel to the border. Perhaps, observers are using a "shearing cue" when there is relative motion parallel to the border when one-half of the display is moving faster than the other half (Nakayama, Silverman, MacLeod, & Mulligan, 1985). We note that this shearing cue is not essential because adding a gap at the border, thereby obscuring the local shearing information, did not alter the threshold. Another possibility is that when motion is parallel to the border, the relative motion between the two halves of the display causes the two halves to be seen as surfaces at different depths, thus helping to segregate the display (Mestre et al., 2001; Rogers & Graham, 1979).

To test the hypothesis that speed discrimination when motion is parallel to the border is aided by the segmentation of the display, we ran the following control experiment. We interspersed two vertical motion configurations: in one case motion was parallel to the boundary, in the other it continued across the boundary. These correspond to Figs. 1C and B, respectively. The observer did not have to judge which of the halves was moving faster, but was asked to determine which way the display was divided. If detection for the parallel motion case is mediated by a segmentation of the display into two parts, then observers should be able to determine which way the display is divided when motion is parallel to the boundary. According to this hypothesis, they would not be able to see this division when the motion was orthogonal to the border. We compared performance in this task to our standard speed discrimination tasks measured when the dots moved across the boundary and parallel to the boundary. We took new speed discrimination data so that we could compare performance across tasks measured at roughly the same time.

The task requiring observers to identify how the display is divided is essentially a yes–no task. Observers likely have a criterion for deciding whether the display is divided vertically or horizontally. In this case, that corresponds to whether the motion was parallel to the border, or whether it was orthogonal to the border. On the other hand, the speed discrimination tasks are two-spatial alternative tasks. In the yes–no task, the detectability d' measured at threshold (82% correct) is 1.8, whereas for the 2AFC task it is 1.3. To facilitate a comparison across tasks, we equated for detectability across these tasks. Because the rest of the data in this paper report speed differences at $d' = 1.3$, we estimated the speed difference corresponding to this value of d' in the yes–no task.

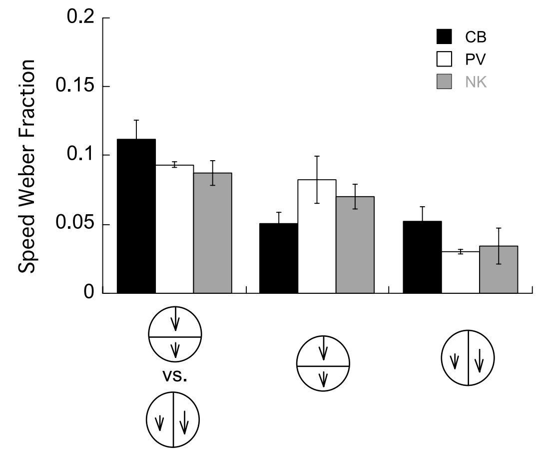

Fig. 6. The role of shear detection in speed discrimination. Thresholds for discriminating whether the display was divided horizontally or vertically are compared to thresholds for discriminating speed when motion crossed the border and when it was parallel to the border. The different colors represent data for our three observers.

The data for this condition are plotted in Fig. 6. The different bar colors represent data for different observers. The leftmost bars are thresholds for the configuration when observers were merely asked to identify whether they had seen a display divided along a horizontal midline or a vertical midline. (These thresholds have been adjusted downward for equal detectability.) The middle bars are speed discrimination thresholds for the case when vertical motion continued across the border and the rightmost bars are for the case when vertical motion was parallel to the boundary. As seen before, observers have lower thresholds when motion is parallel to the border (rightmost bars compared to middle bars). If speed discrimination in this task is mediated by shear detectors that also play a role in parsing surfaces, then performance should be comparable to the case when observers are required to distinguish which way the display is divided. Clearly this is not the case. Speed discrimination thresholds for motion parallel to the boundary (rightmost bars) are significantly lower than thresholds for identifying the orientation of the border (leftmost bars). Observers are quite good at judging speed differences when motion is parallel to the border, but they require much larger speed differences to determine which way the display is divided.

It appears that when the dots move in one direction, the speed differences used in our display are not large enough for the boundary to be visible due to motion parallax. Mestre et al. (2001) showed that speed segmentation occurs at speed differences of about 15–20%, for a criterion of 75% correct performance. Our thresholds, estimated at a stricter 82% correct, have a Weber fraction between 5 and 10% in the parallel condition, which is much smaller than the speed difference required for segmentation. Thus, it is unlikely that the low speed discrimination thresholds we obtain in the parallel condition are due to a segmentation of the surface from motion parallax.

6. Discussion

Our data show that it is hard to access local speed signals when they are seen as belonging to a common motion path. This is consistent with previous findings that it is hard to detect an acceleration signal (Gottsdanker, 1956; Snowden & Braddick, 1991). It is also consistent with studies showing that grouping strongly influences the local speed estimates from a region (Verghese & Stone, 1996).

Our results do not support a second stage velocity integrator that necessarily pools velocity signals within a spatio-temporal window (Nakayama, 1985). The spatial and temporal arrangements for the common motion condition and for the parallel motion condition are essentially the same. If the motion system compared the local velocity signals on either side of the border, speed discrimination thresholds should be identical. Instead, all observers initially have difficulty estimating a speed difference for the common motion condition.

Instead, these results support the premise that the difficulty in accessing local signals when motion continues across the border is due to our past visual experience with objects in motion. Objects typically continue along their paths. Their speed might continuously accelerate due to gravity or continuously decelerate due to friction, but they rarely undergo abrupt changes in speed, while continuing along the same motion path. In our experiments there is no physical boundary marking this speed change. We performed a control experiment to determine whether creating an accretion-deletion boundary (by making the dots disappear on one side of the boundary and reappear on the other side) would improve thresholds for the case when the dots appear to cross the border. This had no effect on thresholds. This result is similar to the case where we tried to segregate the two halves of the display by using dots of different polarity. In both these cases, two regions were discernible, but that did not prevent grouping along the motion path. The one condition that allows the local signals to be accessed is when motion in each half of the display is presented in two non-overlapping temporal intervals.

We also showed that extensive practice allows observers to access local signals on both sides of the border, so that thresholds for the case when motion crosses the border improve with practice and are eventually almost as low as when motion is parallel to the border. This ability to access local signals generally needs to be relearned for new stimulus conditions, such as a different direction of motion, or the addition of dynamic noise. Thresholds are initially elevated for the new conditions but quickly diminish with practice.

The finding that previous visual experience influences speed discrimination in the case of translating dot motion is related to another study that we conducted with rotating and expanding motion (Verghese, 2000). In this case, speed discrimination was unaffected when the flow field motion appeared non-rigid, but was impaired when the dots motion was consistent with rigid rotation or expansion. Together, these show that sensitivity to speed change is strongly influenced by prior visual experience.

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