Asymmetry in Visual Search for Targets Defined by Differences in Movement Speed

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Perception of motion speed was investigated with the visual search paradigm, using human Ss. When searching for a fast target among slow distractors, reaction time was minimally affected as the number of distractors was increased. In contrast, reaction time to detect a slow target among fast distractors was slow and linearly related to the number of distractors. The effect cannot be attributed to differences in temporal frequency, discriminability, or one type of representation that might result from spatiotemporal filtering. An alternative hypothesis that can account for the asymmetry is that speed detectors operate as high-pass filters in the velocity domain. This hypothesis is in agreement with results obtained in psychophysical studies on motion adaptation as well as data from single-cell recordings in nonhuman species.

The visual search paradigm (Treisman & Gelade, 1980) has recently been applied in the study of motion perception (Dick, Ullman, & Sagi, 1987; Ivry & Cohen, 1990; McLeod, Driver, & Crisp, 1988; Nakayama & Silverman, 1986).[1] These studies have consistently indicated that the direction of motion is represented at an early stage of processing. People are able to determine rapidly the presence or absence of a target stimulus that is moving in a different direction from a set of distractor stimuli. Moreover, increasing the number of distractors has minimal effect on response latency. This result has been obtained when the distractor stimuli move in the direction opposite the target (Dick et al., 1987; Nakayama & Silverman, 1986) and when the distractor stimuli move orthogonally to the target (Ivry & Cohen, 1990).

There are two components of motion: direction and speed. The studies cited in the preceding paragraph all focused on the direction component. Correspondingly, most models of motion perception have emphasized the construction of mechanisms that are directionally sensitive (see Nakayama, 1985, for a review). Nonetheless, these mechanisms are also sensitive to a limited range of velocities (e.g., Adelson & Bergen, 1985; van Santen & Sperling, 1984). For example, the basic components of a simple motion detector include two receptors with neighboring receptive fields whose output is combined by a an integrator unit. The outputs, however, do not arrive synchronously at the integrator, but only after one of the signals has been delayed. The integrator is simultaneously activated by both receptors only when a moving stimulus activates the receptor linked to the delay prior to the

other receptor. The asymmetrical design constrains this mechanism to respond to a single direction of motion; however, speed constraints are also imposed by the delay. A stimulus moving in the appropriate direction but too rapidly would produce an output from the second receptor before the delay expires on the output from the first receptor. Similarly, a slow stimulus may fail to activate the second receptor by the time the delay on the first detector elapses. Thus, a single Reichardt detector responds to a limited range of directions and speeds. Presumably, a bank of detectors exists that collectively spans the spectrum of velocities.

Empirical investigations of speed sensitivity can be found in the neurophysiological and psychophysical literature. Velocity-tuning curves are generally quite broad for cells in the striate cortex (Movshon, 1975) and Area MT, a higher visual area implicated in motion perception (Allman, Miezen, & McGuinness, 1985; Maunsell & Van Essen, 1983). These results suggest that the output of individual cells provides only a crude representation of speed. Experiments in human psychophysics, however, have established the high fidelity of velocity perception. McKee (1981) and Sekuler (1990) reported just-noticeable differences in velocity of under 5% for trained observers. Ivry and Diener (1991) obtained similar values with inexperienced subjects. Coarse coding at the neural level can provide efficient representations with minimal cost in resolution (e.g., Hinton, McClelland, & Rumelhart, 1986).

Though they demonstrate that humans can detect small differences in speed, the previous psychophysical studies do not consider the stage of processing at which this information is abstracted. These precise judgments may require elaborate processing of relatively crude inputs. On the other hand, metrical information about speed may be part of the early representation of a moving stimulus, and decision processes

[1] Although we use the term *motion perception* here and throughout this article, the cited evidence almost always involves apparent motion. The displays in the reported experiments all meet the criterion of short-range apparent motion, an illusion believed to activate the same mechanisms activated in real motion perception.

may be able to access this information. In the current set of experiments, we investigate the speed component of motion perception by using the visual search paradigm. Specifically, how efficiently can subjects detect a target that is moving at a different speed from distractor stimuli?

Experiment 1

In the visual search paradigm, reaction time is measured as a function of the number of objects in the display (e.g., Treisman & Gelade, 1980). When reaction time is independent of display complexity, the target feature is said to "pop out." The entire display is assumed to be processed in parallel, reflecting minimal attentional involvement in the detection process. In contrast, when the reaction time increases with the number of distractors, detection of the target is assumed to reflect the operation of a limited-capacity attention process. Additional processing is necessary to differentiate the target from the distractors.

We tested popout for speed differences in two conditions in Experiment 1. The displays in this experiment consisted of a variable number of Xs that oscillated horizontally. On target-present trials, one of the objects oscillated at a different speed from the distractor objects. On target-absent trials, all of the objects in the display oscillated at the same speed. There were two additional variables. First, the number of objects in the display ranged from 5 to 17. Popout of speed differences was inferred from the function relating reaction time to display size. Second, the speeds selected for the target and distractors were reversed between subjects. Subjects in one condition searched for the presence of a relatively fast target among relatively slow distractors. The target and distractor speeds were reversed for the other subjects. In this condition, the search was for a slow target among fast distractors. Assuming that we have chosen sufficiently distinct speeds, we expected that reaction time would be independent of array size.

Method

Subjects. Twenty-five undergraduates at the University of California, Santa Barbara (UCSB), participated in the experiment in partial fulfillment of a course requirement. The subjects had normal or corrected-to-normal vision.

Apparatus and stimulus displays. The stimuli were presented on a Zenith ZCM-1490 monitor controlled by an AST Premium/286 computer. Each object in the display was an achromatic X (approximate luminance: 61 cd/m^2) presented on a black background (luminance < 1 cd/m^2). On the basis of a viewing distance of 100 cm, each X subtended a visual angle of approximately 10 × 14 min of arc.

A display consisted of either 5, 9, 13, or 17 Xs. Apparent motion was created by presenting a different graphics screen every 50 ms in which each object was displaced in the horizontal direction. The total amplitude over which an object moved was 41' of arc. Oscillatory motion was created by reversing the movement direction when an object reached the end of this distance. The starting phase was randomly selected for each object, as was the initial direction of movement (e.g., left or right). Speed was manipulated by varying the distance the objects were displaced. Objects moving at the fast speed were displaced approximately 8' of arc each screen and required 11 screens (500 ms) to complete each cycle. Objects moving at the slow speed were displaced 4' of arc and required 21 screens (1,000 ms) to

complete each cycle. These displacements correspond to speeds of 2.8°/s and 1.4°/s. The small displacements and 50-ms stimulus onset asynchrony (SOA) fall well within Braddick's (1974) criterion for short-range apparent motion, and the simulated motion was very smooth. Oscillatory motion was chosen so that the display remained visible until the subject responded.

Each X was initially positioned at a random location on the screen. These positions were constrained to always require a minimum distance of at least 1.7° and 1.2° between neighboring objects in the horizontal and vertical directions, respectively. The actual spacings were usually much larger. The spacing restrictions were included to ensure that there was no confusion in establishing the correspondence between successive presentations of the same object and to eliminate the possibility of collisions between moving stimuli. Coupled with the random setting of initial phase and direction, these constraints minimize the possible formation of higher order perceptual units (Ivry & Cohen, 1990). At any given time, half of the distractors could be expected to move in one direction and the other half in the opposite direction.

Design. Twelve of the subjects were assigned to the fast target condition. The other 13 were assigned to the slow target condition. For the fast target condition, all of the distractor Xs moved at the slow speed of 1.4°/s. On target-present trials, the speed of one of the objects was set at 2.8°/s. The speeds for the target and distractor were reversed for subjects in the slow target condition. Here, one object moved at 1.4°/s on target-present trials among distractors oscillating at 2.8°/s.

Each subject completed one practice block of 48 trials and four test blocks of 96 trials each. In each block there were 12 trials of each of eight conditions (4 display sizes × 2 target present–absent). The practice block consisted of six trials of each condition.

Procedure. Each trial began with the illumination of a fixation point (an asterisk) in the center of the screen. One s later, the stimulus display appeared and remained visible until the subject responded. The clock for measuring reaction time began 50 ms later, when movement first occurred. Subjects responded by pressing one of two keys mounted on a board interfaced with the computer. The left-hand key was labeled "PRESENT," and the right-hand key was labeled "ABSENT." Responses were made with the index fingers of both hands. If the response was incorrect, the message "ERROR!" was presented in large letters for 2 s. The intertrial interval was 2 s.

The instructions emphasized that reaction time was of primary interest and that subjects should not be concerned if they made a few errors in each block. Error summary was provided at the end of each block. If the error rate was 5% or less, subjects were encouraged to go faster. If the error rate was greater than 5%, the experimenter repeated that the primary interest was in reaction time but that accuracy should be maintained.

Results and Discussion

The reaction time data for trials in which the response was correct is summarized in Figure 1. A strong asymmetry can be seen between the fast and slow target conditions. There is little increase in reaction time on target-present trials when a fast target is detected among slow distractors, especially when the arrays contain more than five objects. In contrast, search for a slow target among fast distractors is much slower overall and is increasingly slowed by the inclusion of more objects in the display.

We conducted separate statistical analyses for target-present and target-absent trials. This strategy was chosen because previous research with the search paradigm has indicated that
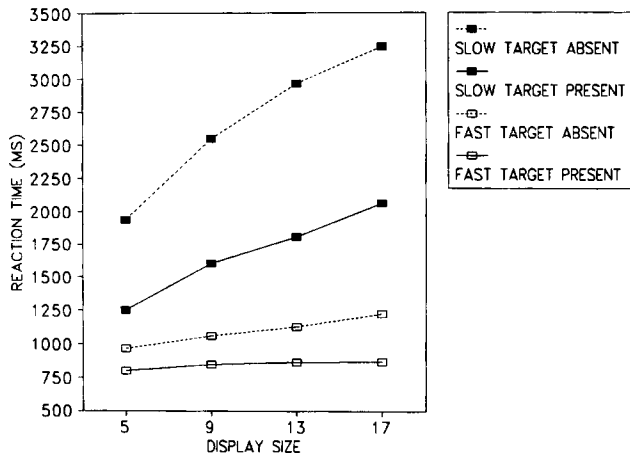
Figure 1. Mean reaction times as a function of display size for Experiment 1. (Standard errors of the means for Display Sizes 5, 9, 13, and 13, respectively, are fast–present, 61, 58, 59, 55; fast–absent, 67, 85, 92, 124; slow–present, 74, 127, 133, 175; and slow–absent, 164, 249, 320, 409.)

target-absent functions may show a display-size effect even when the target pops out (e.g., Ivry & Cohen, 1990; Treisman & Gelade, 1980). We ran two 2 × 4 mixed-variable analyses of variance (ANOVAs), with the between-subjects variable the speed of the target and the within-subjects variable the size of the array. In the target-present analysis, main effects were observed for target speed, $F(1, 23) = 35.29$, $p < .001$, and array size, $F(3, 69) = 37.95$, $p < .001$. Most important, the interaction was significant, $F(3, 69) = 27.24$, $p < .001$, indicating that the effect of array size was larger when the target was slow than when the target was fast. The results were similar for the target-absent analysis. The main effects were significant, as was the interaction, $F(3, 69) = 14.07$, $p < .001$. Again, the search function rose more rapidly for the slow target condition.

The differences between the two target speeds can be quantified by slope estimates for each function in Figure 1. The slopes for the subjects in the fast target condition were 5 and 20 ms/item for the target-present and target-absent trials, respectively. The comparable figures for the slow target conditions were 63 and 110 ms/item. A slope ratio of 1:2 has been hypothesized to reflect the operation of a limited-capacity, self-terminating attentional process (e.g., Ivry & Cohen, 1990; Treisman & Gelade, 1980). The ratio of .57 for the slow target condition approximates this predicted value. The ratio is only .24 for the fast target condition. As can be seen in Figure 1, most of the increase in the target-present function occurs between display sizes of 5 and 9. There is only a 20-ms increase as the display size increases from 9 to 17.

Regression analysis further supports the conclusion that there is a processing asymmetry between the fast and slow target conditions. The limited-capacity attention process implies a linear relationship between reaction time and array size. The proportion of variance that can be accounted for by a linear component is almost 99% when the target is present in the slow condition. The value for the fast target condition

is 83%. This figure is inflated by performing the calculations on the mean data. The proportion of variance exceeds 75% for only 3 of the subjects when a fast target is detected among slow distractors, whereas this criterion is exceeded by 12 of the 13 subjects in the slow condition.

The differences obtained in the reaction time were evident in the error data as well. For the fast target condition, the error rates were 3.3% and 2.6% for the present and absent trials, respectively. For the slow target condition, the error rates were 11.4% and 2.6%. Moreover, although there was no consistent relationship between errors and display size for the fast condition, errors were directly related to display size in the slow condition. In increasing order for the four array sizes, the error rates were 2.4%, 8.3%, 14.7%, and 20.4%. Thus, the differences in reaction time cannot be accounted for on the basis of a speed–accuracy trade-off. Instead, it appears that the reaction time differences between the fast and slow conditions would have been even greater if the error rates had been constant.

The results of Experiment 1 provide partial support for the hypothesis that speed is part of the early representation of motion information. A fast target was rapidly detected among a display of slow distractors, and reaction time was relatively independent of display size. The time to detect a slow target, however, was linearly related to the number of objects in the display, implicating a limited-capacity search process.

This asymmetry argues against a simple model of speed detectors underlying performance in this task. Drawing an analogy to popout for other dimensions such as color or orientation, we expected that there were detectors (or, in Treisman's terminology, *feature maps*) tuned to certain speeds in the same way that there appear to be detectors tuned to certain hues or orientations. For example, an array of speed detectors could be constructed by varying the spacing or temporal delay of the elements that form Reichardt detectors. Assuming that the differences between the target and distractor speeds were sufficiently different to produce activation on different sets of detectors, we expected symmetrical popout. During search for a fast target, positive responses would be made if activation was recorded in the fast detectors. Slow targets would be detected through activation of the slow detectors. The results do not support this simple model.

Sekuler (1990) recently investigated texture segregation when regions are defined by speed differences. The stimuli consisted of two regions of dots moving at different speeds. The speed of one region, the base, was held constant, and the speed of the variable region was adjusted to determine the slower and faster thresholds at which segregation occurred. Sekuler (1990) reported two asymmetries in this task. First, for low base speeds, segregation occurred with a smaller difference between the two regions when the variable region was made faster than the base speed as opposed to when the variable region was made slower. In other words, subjects were more sensitive to increments in speed. Second, the reverse was found for high base speeds. In these conditions, subjects were more sensitive to decrements in speed.

The preferential sensitivity to increments with low base speeds is similar to the results of Experiment 1 in which a fast target popped out from slow distractors. In Experiment 2 we

test for the second asymmetry. Namely, will the asymmetry between fast and slow targets reverse with faster speeds?

Experiment 2

Experiment 2 replicates Experiment 1, with one change. The speeds of the moving objects were increased to either 6.4°/s or 3.2°/s. The best estimate provided by Sekuler (1990) of the crossover point at which the speed sensitivity bias changes from increments to decrements is approximately 5.8°/s. This estimate must be qualified because it is based on results from only one experienced subject. Moreover, the value shifts as a function of display density. Although we would have preferred to use speeds that are well above the 5.8°/s crossover estimate, our equipment limited the range of speeds we could test. The 6.4°/s speed is about the fastest speed that can be effectively simulated on a computer monitor given the constraints of a minimum SOA of 50 ms and maximum displacement of 20'. Nonetheless, we expected that if the same mechanisms were underlying performance in the visual search task as in Sekuler's texture task, then the asymmetry observed in Experiment 1 should be reversed or reduced in Experiment 2.

Method

Subjects. Sixteen undergraduates were recruited in the same manner as in Experiment 1. None had participated in the previous experiment.

Stimulus displays. There were four changes in the displays for Experiment 2. First, the faster speeds were simulated by displacing the objects over greater distances in each screen. Objects moving at 6.4°/s were displaced just over 19' of arc every 50 ms. Objects moving at 3.2°/s were displaced half this distance. Second, each object oscillated over an amplitude of 1.6°, with the faster objects taking six screens to span this distance and the slower objects taking 11 screens. Third, the minimum horizontal distance between any pair of objects was increased to 3.6° of arc to eliminate the possibility of false correspondences. Fourth, the previous change required that we reduce the array sizes to 3, 7, 11, and 15 so that the algorithm for locating the objects could produce an acceptable set of locations for each trial.

Design and procedure. The subjects were divided into two groups of 8 subjects each. For one group, the target moved at a speed of 6.4°/s, and the distractor moved at 3.2°/s. The target and distractor speeds were reversed for the other group. All other aspects of the procedure were identical. Subjects completed one practice block of 48 trials and four test blocks of 96 trials each.

Results and Discussion

The reaction time data are shown in Figure 2. Only correct responses are included. The results show an asymmetry similar to that obtained in Experiment 1. Subjects are much faster in determining the presence or absence of a fast target in a display of slow distractors than in the reverse. The Speed × Display Size interaction was significant for both target-present trials, $F(3, 42) = 13.56$, $p < .001$, and target-absent trials, $F(3, 42) = 4.49$, $p < .01$. On both types of trials, the search function rose much more rapidly when the slow speed was the target.

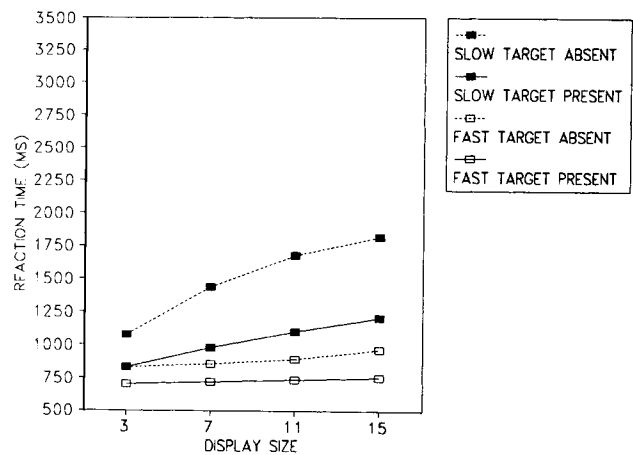The mean slopes for the fast target condition were approx-

Figure 2. Mean reaction times for Experiment 2. (Standard errors of the means for Display Sizes 3, 7, 11, and 15, respectively, are fast-present, 48, 50, 55, 53; fast-absent, 73, 103, 104, 143; slow-present, 76, 102, 124, 127; and slow-absent, 110, 216, 289, 362.)

imately 4 ms/item and 11 ms/item for the target-present and target-absent trials, respectively, a ratio of .36. The comparable values for the slow target conditions were 31 ms/item and 63 ms/item, forming a ratio of .50. More than 93% of the variance for all four functions in Figure 2 is accounted for by a linear component; however, this analysis of the mean values is not reflected in a regression analysis of the individual functions. For the fast target condition, a linear component accounts for 75% of the variance on four of the target-present and two of the target-absent functions. In contrast, all of the target-present and five of the target-absent functions meet this criterion for the slow target condition. The task appears to require a limited-capacity search process for the slow target. In contrast, detection of the fast target is minimally affected by display size.

The error data further demonstrate the better performance of the subjects in the fast target condition. The overall error rate for these subjects was 1.5%. The overall error rate for the slow target condition was 5.5%. Seventy percent of these errors were trials on which the subject missed a target, and this type of error increased as the display size became larger. Again, the error data suggest that the difference between the fast and slow target conditions would be greater if error rates were equal.

The reaction time and error data of Experiment 2 replicate at faster speeds the asymmetry found in Experiment 1. There does not appear to be a reversal of this asymmetry, an effect Sekuler (1990) found in a texture segregation task. It is possible that we failed to obtain a reversal because our speeds were not fast enough. The slopes for the slow target conditions in Experiment 2 were about half those obtained in Experiment 1, suggesting that the search task was easier for subjects in this condition of Experiment 2. A between-experiment comparison of the fast target conditions, however, does not indicate that this condition became more difficult with faster speeds. The overall reaction times are faster, and the slope values were slightly lower. If the asymmetry were to reverse,

we would expect the fast target search to become more difficult and the slow target search to become easier. Changing the range of speeds led only to an improvement in the slow target condition. This effect may be the result of choosing a slow target speed in Experiment 1 for which velocity discrimination is suboptimal (McKee, 1981).

Experiment 3

In the first two experiments, we defined the distinction between the target and distractors as a difference in speed. In these experiments, however, speed and temporal frequency were confounded. We chose to simulate the different speeds by varying the displacement distance of each successive presentation of the objects while holding constant the amplitude of oscillation. Thus, the frequency of oscillation was always higher for the fast target than for the slow target. If there are detectors sensitive to temporal frequency (or changes of direction), then the fast target might be favored because it would lead to greater activation of these detectors.

Several theorists have proposed that velocity perception is the result of processing in detectors sensitive to temporal frequency rather than in detectors tuned to speed per se (Sekuler, Pantle, & Levinson, 1978; Smith, 1987; Tolhurst, Sharpe, & Hart, 1973). The evidence for these models is primarily derived from experiments with periodic stimuli in which temporal frequency and speed can be manipulated independently. For example, Pantle (1974) found that the magnitude of motion aftereffects was roughly invariant when the temporal frequency of the adapting stimulus was constant, despite variations in the speed of the adapting stimulus. Thompson (1981), however, reached the opposite conclusion, namely that aftereffect functions were similar when the speed of the adapting stimulus was held constant over a range of temporal frequencies. A resolution to this contradiction may be found in the results of Smith (1987). He observed that random variations in temporal frequency had minimal effect on performance on a velocity-discrimination task for velocities below 10°/s, thus implicating speed detectors. Judgments of faster stimuli appeared to depend on other cues, including temporal frequency. The fastest speeds in Pantle (1974) were above 12°/s, and it was with these stimuli that motion aftereffects were constant for different temporal frequencies.

Given that the speeds tested in Experiments 1 and 2 were less than 10°/s, it is unlikely that the search asymmetry reflects differences in temporal frequency. Nonetheless, we have tested this hypothesis in two experiments. First, in a pilot experiment, temporal frequency was equated for all of the objects in a display. The difference in speed was simulated as in Experiment 1, with the fast objects moving twice as far per displacement as the slow objects. The number of screens in an oscillatory cycle was held constant, however, thus equating temporal frequency. Of course, this introduced a confound between speed and amplitude of oscillation because the amplitude of oscillation was twice as great for the fast objects. The search asymmetry was obtained in this pilot experiment. When a fast target was searched for among slow distractors, mean reaction times on target- present trials were 1,175,

1,206, 1,213, and 1,194 ms for display sizes of 5, 9, 13, and 17. The mean reaction times to detect a slow target among fast distractors were 1,827, 2,156, 2,386, and 2,635 ms.[2] Both the main effect of target speed and the Target Speed × Array Size interaction were highly significant ($p < .001$). Reaction time increased with display size in the slow target condition only (fast target slope, 1.6 ms/item; slow target slope, 66.4 ms/item).

An alternative control for temporal frequency is pursued in Experiment 3. In this experiment, temporal frequency was randomized within a display. If fast targets were favored in the previous experiments because of their higher temporal frequency, then the advantage should be lost when this cue is eliminated.

Method

Subjects. Twenty undergraduates at the University of California, Berkeley (UCB), participated in partial fulfillment of a course requirement. None had been in the previous experiments.

Stimuli. As in Experiment 2, fast objects moved at a speed of 6.4°/s, and slow objects moved at a speed of 3.2°/s. The major change in Experiment 3 was that the amplitude of oscillation was randomly set for each object on each trial. This was accomplished by varying the number of screens required to complete each half cycle. The number of screens for a fast object was randomly set between 4 and 7, corresponding to an amplitude range of 77'–135' of arc. The number of screens for a slow object was randomly set between 4 and 14, corresponding to an amplitude range of 38'–135' of arc.

We wanted to reduce correlations between temporal frequency, speed, and amplitude of oscillation. Thus, we chose to vary randomly the number of screens traversed by each object and to use different ranges for the fast and slow objects. The same minimum number of screens was necessary to ensure that a target and distractor could have the same temporal frequency. The different maxima were chosen so that the largest possible amplitude of oscillation for fast and slow objects would be equal.

There were two other changes in Experiment 3. First, the stimulus displays were presented on a Sony Multi-Scan HG monitor. Second, the objects were filled achromatic square boxes rather than Xs. Each side of the squares subtended approximately 6' of arc. This ensured that successive presentations of all of the objects would always illuminate nonoverlapping sets of pixels because the minimum displacement per screen was always greater than 9' of arc. Thus, any potential artifacts introduced by phosphor integration were eliminated.

Design and procedure. Ten subjects were assigned to the fast target condition, and the other 10 were assigned to the slow target condition. Each subject completed one practice block of 48 trials and four test blocks of 96 trials.

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[2] The mean intercepts for the fast and slow target conditions were 1,175 ms and 1,560 ms, respectively. These values are larger than those obtained in Experiment 1 despite the identity in simulated speeds. This might suggest that temporal frequency is important. We believe, however, that the increase in intercept occurs because the objects reversed direction every third displacement in the control experiment in contrast to reversals every 11 or 21 displacements in Experiment 1. We have informally observed that up to a point, the intercept is reduced as the number of screens per cycle is increased, without a change in slope.

Results and Discussion

The mean reaction time data are presented in Figure 3. As in the preceding experiments, detection of the fast target is relatively invariant of display size, whereas the time to detect the slow target increases with display size. We found main effects of group—target-present trials, $F(1, 18) = 5.30$, $p < .05$; target-absent trials, $F(1, 18) = 6.53$, $p < .02$—and array size—target-present trials, $F(3, 54) = 10.51$, $p < .001$; target-absent trials, $F(3, 54) = 6.30$, $p = .001$). Most important, the interaction of these two variables was significant in both analyses: Target-present trials, $F(3, 54) = 5.01$, $p < .01$; target-absent trials, $F(3, 54) = 7.96$, $p < .001$. The functions rose more steeply in the slow target condition.

These results are supported further by the regression and error data. The slopes on the target-present trials were 6 ms/ item for the fast target condition and 30 ms/item for the slow target condition. The slope for the fast target condition on the absent trials was negative, whereas the comparable slope for the slow target condition was 51 ms/item. The mean error rates on target-present trials were 6.9% and 13.5% in the fast and slow target conditions, respectively. In each condition, errors increased with display size, but the effect was most marked in the slow target condition, in which the error rate peaked at 23.3% for the largest array size.

The asymmetry does not appear to be the result of differences in temporal frequency. We found the asymmetry in both the pilot experiment, in which temporal frequency was equated, and in the current experiment, in which temporal frequency was randomly manipulated. It is of interest that the intercepts were elevated in the current experiment as opposed to Experiment 2. For example, the mean intercept in the fast target-present condition rose from 690 ms in Experiment 2 to 878 ms in Experiment 3. This increase may be due to methodological differences such as the reduction in pixels (and, correspondingly, brightness) for the square objects. Alternatively, random variation in temporal frequency

Figure 3. Mean reaction times for Experiment 3. (Standard errors of the means for Display Sizes 3, 7, 11, and 15, respectively, are fast–present, 71, 60, 78, 63; fast–absent, 82, 83, 88, 84; slow–present, 190, 216, 215, 249; and slow–absent, 284, 359, 450, 474.)

may create additional noise in either perceptual or decision processes required for this task. Nonetheless, variation in temporal frequency appeared to have negligible effect on any of the slope values.

Experiment 4

Treisman and Gormican (1988) argued that asymmetries in visual search may occur because of quantitative differences in activation generated by displays involving the preferred and nonpreferred targets. According to this account, both the target and the distractors activate the same set of detectors. The degree of activation, however, reflects quantitative differences between the features. For example, long lines produce more activation than short lines. Responses are made on the basis of the difference in the output of these detectors between trials in which the target is present and trials in which the target is absent.

This difference can be quantified as a Weber fraction, or $|Op - Oa|/Oa$, where Op and Oa represent total detector output on target-present and target-absent trials, respectively. The asymmetry arises because the favored target produces a greater difference between present and absent trials. Consider the asymmetrical finding that a long line is much easier to find among short distractors than the reverse. For a quantitative example, we assign an activation value of 4 for each long line and an activation value of 1 for each short line. When searching for a long line among short distractors, the Weber fraction for displays of 3 is $|6 - 3|/3 = 2.0$. The Weber fraction for the same size display when the target is the short line is only $|9 - 12|/12 = 0.25$. Thus, the presence of the long target produces a greater difference than the presence of a short target.

We test this account of asymmetry in visual search for speed differences in Experiment 4. We test the quantitative-output hypothesis by equating the Weber fraction for fast and slow target conditions in the manner used by Treisman and Gormican (1988, Experiment 1a). They found that this manipulation eliminated the search asymmetry for line length.

Method

Subjects. Sixteen subjects were recruited from the graduate and undergraduate populations at UCSB (Experiment 4a) and UCB (Experiment 4b). The subjects received course credit or were paid $7 for their participation.

Stimuli. Two different ranges of speed were tested. In Experiment 4a, the distractors always moved at 2.8°/s. The target speed was set to either 4.2°/s or 1.4°/s, a difference of 1.4°/s from the distractor speed. The objects were all Xs and oscillated over a fixed amplitude of 41' of arc for the slow target and distractors and 38' of arc for the fast target. The latter amplitude was the best approximation we could achieve with our method of simulating motion. Display sizes of 5, 9, 13, and 17 were tested.

The Weber fraction is equated for the fast and slow target conditions because the distractors are matched and the difference between the target and distractor speeds are the same ($|1.4–2.8| = |4.2–2.8|$). This method of equating similarity rests on the assumption that there is a linear relation between the speed of the stimuli and the internal code that represents this dimension. Treisman and Gormican (1988)
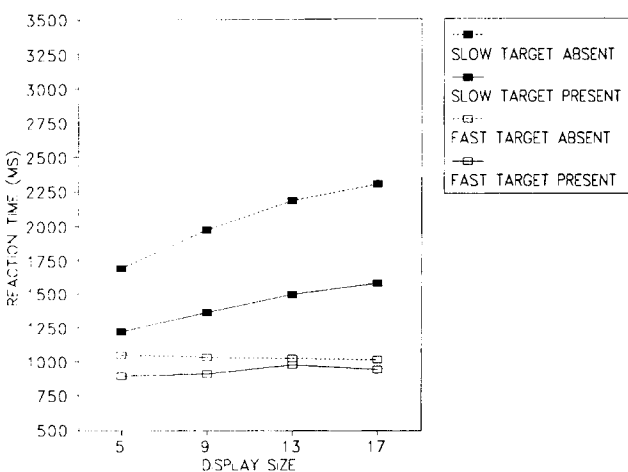
successfully eliminated the line-length asymmetry with the same assumption.

Nonlinear functions of velocity perception, however, have been proposed (McKee, 1981; Sekuler, 1990). For example, in a velocity-discrimination task, McKee (1981) found that the ratio relating the difference threshold to velocity was constant for speeds ranging from approximately 2°/s to 11°/s (see also Smith, 1987). For speeds below this range, the ratio increased, suggesting nonlinearities at the lower end of the speed continuum. Thus, in Experiment 4b, we selected three speeds that were all above 2°/s. The distractor speed was set at 4.6°/s. The fast target moved 6.4°/s, and the speed of the slow target was 2.8°/s. Equating the amplitude of oscillation as best as possible produced amplitudes of 1.6° for the distractors and fast target and 1.5° for the slow target. The objects were filled squares as in Experiment 3, and successive presentations of a given object illuminated disjoint sets of pixels. Display sizes of 3, 7, 11, and 15 were tested.

Design and procedure. Eight subjects were tested with the lower range of speeds (Experiment 4a), and the other 8 subjects were tested with the higher range of speeds (Experiment 4b). Within a range, each subject completed two test blocks in the slow target condition and two test blocks in the fast target condition. Each test block consisted of 96 trials. The first block of each condition was preceded by a practice block of 48 trials. The order of conditions was counterbalanced: Half of the subjects were tested on the slow target condition before the fast target condition, and the order was reversed for the other half of the subjects.

Results and Discussion

There were no differences in performance as a function of the order of conditions, so the data were collapsed over this factor. Figures 4a and 4b present the results for the fast and slow target conditions of Experiments 4a and 4b, respectively. Unlike the results obtained by Treisman and Gormican (1988) with line length, equating the Weber fraction did not eliminate the asymmetry in speed. Reaction times were much faster for the fast target condition. This was obtained when the target was either present—Experiment 4a, $F(1, 7) = 23.67$, $p < .002$; Experiment 4b, $F(1, 7) = 39.56$, $p < .001$—or absent—Experiment 4a, $F(1, 7) = 24.50$, $p < .002$; Experiment 4b, $F(1, 7) = 10.70$, $p < .02$. The interaction of target speed and display size was significant for both types of responses in Experiment 4a: Present, $F(3, 21) = 3.29$, $p < .05$; absent, $F(3, 21) = 8.26$, $p < .001$. With the higher range of speeds in Experiment 4b, the interaction was significant only for the trials in which the target was absent, $F(3, 21) = 3.58$, $p < .05$.

The regression analyses indicate that a limited-capacity attention process was required in all of the conditions. For the target-present trials, we obtained slopes of 22 ms/item and 63 ms/item in Experiment 4a for the fast and slow target conditions, respectively. The slopes for these trials in Experiment 4b were 39 ms/item and 54 ms/item. Of course, the slopes of the target-absent trials were much larger. We assume that these positive slopes, even in the fast target conditions, are the result of the reduced difference between the target and distractor speeds in comparison to the preceding experiments. In Experiments 1–3, the speed of the target and distractors always differed by a factor of two, and this difference was sufficient to produce popout for the fast target. The ratios are considerably smaller for the fast target conditions in Experi-
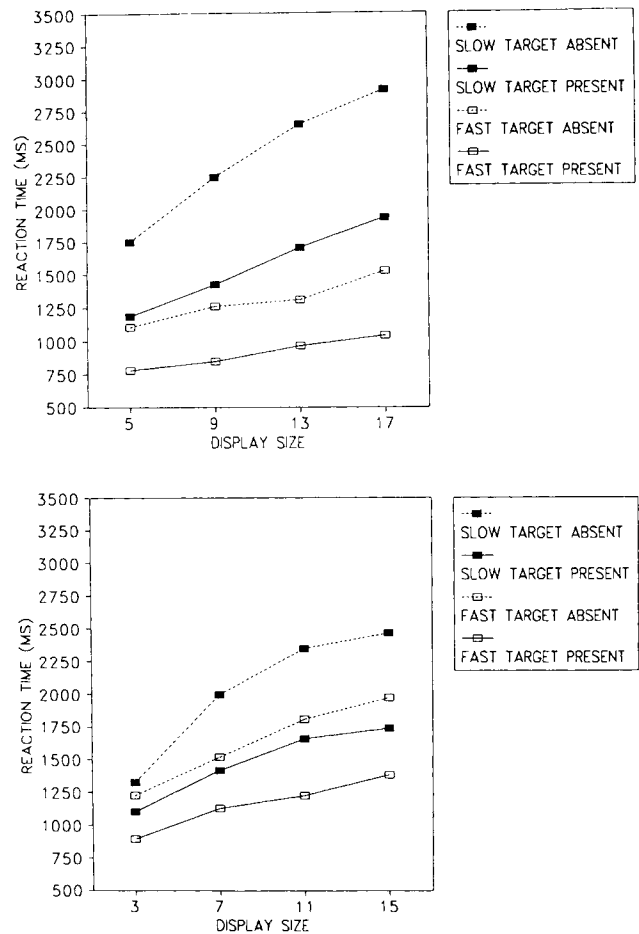
Figure 4. Mean reaction times for Experiments 4a (top panel) and 4b (bottom panel). (For Experiment 4a, standard errors of the means for Display Sizes 3, 7, 11, and 15, respectively, are fast–present, 41, 34, 61, 69; fast–absent, 101, 109, 91, 144; slow–present, 80, 105, 179, 250; and slow–absent, 153, 232, 334, 374. For Experiment 4b, they are fast–present, 44, 79, 87, 118; fast–absent, 70, 128, 192, 220; slow–present, 55, 109, 109, 129; and slow–absent, 67, 164, 207, 264.)

ments 4a and 4b as well as for the slow target condition in Experiment 4b. Slopes in visual search tasks increase as the difference between the target and distractor becomes smaller (Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Treisman & Gormican, 1988).

The error data are in general agreement with the two points discussed earlier: Namely, a limited-capacity process was invoked in all conditions, and of greater interest in this study, there was an asymmetry that favored detection of the fast target. Most of the errors were trials in which subjects failed to detect the target. In Experiment 4a, miss rates were 8.5% for the fast target condition and 12.9% for the slow target condition. In Experiment 4b, the miss rates were 12.9% and 16.5% for the fast and slow target conditions, respectively. The Target Condition × Array Size interaction was significant for both groups: Experiment 4a, $F(3, 21) = 3.71$, $p < .05$; Experiment 4b, $F(3, 21) = 3.14$, $p < .05$. These findings emphasize again that the search asymmetry persisted even

when the Weber fraction was equated for the slow and fast target conditions across two ranges of speeds.

In summary, Experiments 4a and 4b suggest that the speed asymmetry does not reflect quantitative differences in the output of a single set of detectors. An alternative version of the quantitative-output hypothesis might be developed that considers signed differences rather than absolute differences. That is, the total activity generated by a display might be computed and the response based on whether the total corresponds to a display composed of distractors alone or a display composed of distractors plus the target. For a given display size, the fast target condition produces greater activation when the target is present than when it is absent, whereas inclusion of the target produces smaller activation in the slow target condition. It may be easier to judge that a display has more activity than average than it is to judge that a display has less activity than average.

A model developed on these grounds would have difficulty accounting for why the asymmetry becomes larger with increasing display sizes. The difference between target-present and target-absent trials would be constant for both the fast and slow target conditions. The background activity, however, will increase with display size, thus reducing the proportional change in activity between present and absent trials. A more reasonable prediction for this model would be that the asymmetry would become smaller with increasing display size. Of course, this is opposite the obtained results.

Experiment 5

A different account of the speed asymmetry can be developed by considering the representations created by moving objects. Computational models of motion perception have emphasized that motion detectors must integrate information over both space and time (e.g., Adelson & Bergen, 1985; van Santen & Sperling, 1984; Watson & Ahumada, 1985). It is reasonable to assume that there are spatial and temporal limits to this integration process. In Ivry and Cohen (1990), we argued that popout is obtained only for short-range apparent motion and not for long-range apparent motion because the successive displacements in the latter condition exceed the spatial limit of the integrator. We have used displacements that fall within the short-range criterion in all of the current experiments. Moreover, we found the asymmetry with different base speeds (i.e., different displacements), suggesting that the spatial factors of the integration process do not account for the effect.

On the other hand, consider the hypothetical effects of a temporal limit on the integration process. Suppose that the representation produced by a motion detector is a transformation of the stimulus passed through a filter in the time domain. For example, consider the representation of a square as it moves from left to right. A temporally integrated representation of this object would not be a square but rather a series of squares linked into a horizontally oriented rectangle. That is, an unoriented object such as a square is temporally blurred into a highly oriented object, the direction of orientation lying along the axis of motion. The orientation is not captured in a static, spatial representation but rather the dynamic integration over successive spatial representations (Adelson & Bergen, 1985). The degree of orientation, or elongation, is a function of both the temporal width of the filter and the speed of the object. For a fixed velocity, the spatiotemporal representation becomes more elongated as there is an increase in the duration over which integration occurs. In the preceding experiments, the time between successive presentations of each object was constant across speeds, so this variable should not produce different effects for fast and slow targets.

In contrast, consider how different speeds are treated by a spatiotemporal filter. The output from a spatiotemporal filter will create representations that become elongated along the direction of motion. Most important, over a fixed period of time, the integrated representation of an object moving at a fast speed will always be more elongated than that produced by the same object moving at a slow speed. Detectors sensitive to the spatial aspects of these spatiotemporal representations could underlie the speed asymmetry.

In a sense, we are proposing that the speed asymmetry is analogous to an asymmetry observed with line length. In both visual search (Treisman & Gormican, 1988) and texture-discrimination tasks (Beck, 1974), detection of a long line among short lines is much easier than the detection of a short line among long distractors. If the temporally filtered outputs of motion detectors form elongated spatiotemporal representations, then search for a fast target among slow distractors is similar to search for a long line among short lines.

We do not believe that there is an identity between the spatiotemporal representations created by moving objects with static, spatial representations. For example, as found in Experiment 4, the asymmetry observed with speed has characteristics different from the asymmetry observed with stationary stimuli that vary in line length (Treisman & Gormican, 1988). Nonetheless, we assume that the spatial aspect of the spatiotemporal representations is not independent of the spatial representations for static displays. Given this assumption, the spatiotemporal filter hypothesis would predict that spatially elongated distractors should interfere with the ability to detect a less elongated target because the spatiotemporal representations are similar.

In a pilot experiment, the target was a short line, and it moved at 2.8°/s. The same shape was used for half of the distractors, and they moved at 1.4°/s. The other half of the distractors were a longer line, and these objects remained stationary. The search function was relatively flat, resembling that obtained for the fast target in Experiment 1.

This display, however, may not be the appropriate test because previous research (Dick et al., 1987; Ivry & Cohen, 1990; McLeod et al., 1988) has shown that stationary targets are ignored in motion search tasks. Thus, in Experiment 5, we used the same two distractors but made both move at the slow speed. Our prediction is that the inclusion of slow-moving, elongated distractors will interfere with the detection of a relatively unoriented fast-moving target. The interference will occur because after spatiotemporal filtering, there will be more similarity between the target and the elongated, slow-moving distractors than there is between the target and dis-

tractors when the objects are identical in form (Duncan & Humphreys, 1989).

The addition of the elongated distractors introduces another variable into the design: The displays will contain two different distractors. Duncan and Humphreys (1989) showed that increasing distractor heterogeneity can produce an increase in search slopes. To assess the effect of heterogeneous distractors, we tested a group of subjects with displays containing two distractors, half with the same shape as the target and half unoriented. The Duncan and Humphreys model predicts that search of these displays should be relatively slow. In contrast, applying the filtering process described previously leads to the prediction of minimal interference on these trials. The spatiotemporal representation of the fast target should be more elongated than the representations of either type of distractor.

Method

Subjects. Twenty-two undergraduates at UCSB were recruited as in Experiment 1.

Stimuli. The target speed of 2.8°/s and the distractor speed of 1.4°/s were simulated as before. The target moved 8' of arc and each distractor moved 4' of arc every 50 ms. The target and half of the distractors were a short line, measuring approximately 10' × 2' of arc. For separate groups of subjects, the other distractors were either longer lines or Xs. The elongated lines measured 41' × 2' of arc, a fourfold increase in width:height ratio from the target and other half of the distractors. The Xs measured 10' × 14' of arc. The number of pixels illuminated for the elongated lines and the Xs were approximately equal. All of the objects oscillated in the horizontal direction. For the short and long lines, this direction is parallel to their primary axis.

The amplitude of oscillation for the fast target and slow distractors with a high width:height ratio was 82'. Because frequency of oscillation was held constant, the amplitude for the slow distractors with a low width:height ratio was 41' because of their decreased length. Display sizes were 3, 7, 11, and 15.

Design and procedure. Twelve of the subjects were tested with the short- and long-line distractors (elongated group), and 10 were tested with short-line and X distractors (unoriented group). The data for 1 subject in the elongated group was not included in the analysis because of long reaction times. Each subject completed one practice block of 48 trials and four test blocks of 96 trials.

Results and Discussion

The search functions are presented in Figure 5. Note the change in scale from the previous figures. On the target-present trials, main effects were obtained for array size, $F(3, 57) = 7.22, p < .001$, and group, $F(1, 19) = 13.81, p < .002$. The Size × Group interaction approached significance, $F(3, 57) = 2.21, p < .10$. On target-absent trials, both main effects were significant—array size, $F(3, 57) = 32.62, p < .001$; group, $F(1, 19) = 13.15, p < .002$—as was their interaction—$F(3, 57) = 3.48, p < .05$. Despite the identity of target and distractor speeds for the elongated and unoriented groups, reaction times were much slower for the former group. Moreover, the interference created by the inclusion of elongated distractors became greater as display size increased, an effect that was significant for the target-absent trials and marginally significant for the target-present trials. The mean slopes on the
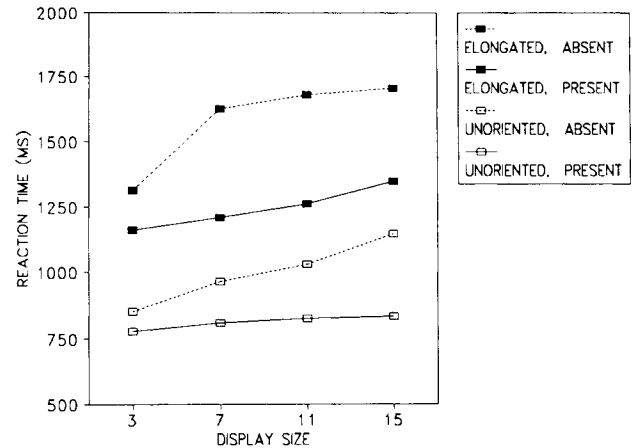

Figure 5. Mean reaction times for Experiment 5. (Standard errors of the means for Display Sizes 3, 7, 11, and 15, respectively, are unoriented-present, 28, 30, 28, 31; Unoriented absent: 55, 73, 85, 111; Elongated present: 74, 120, 123, 124; Elongated absent: 102, 166, 137, 153.)

target-present and target-absent trials for the elongated group were 16 ms/item and 31 ms/item, respectively, forming a positive:negative ratio of .50.[3] The comparable values for the unoriented group were 5 ms/item and 23 ms/item. Although there are several methodological differences, the slope values for this group were comparable to those obtained in Experiment 1 with identical target and distractor speeds. This finding is contrary to that predicted if the interference effect is solely due to the inclusion of heterogeneous distractors (Duncan & Humphreys, 1989).

Error rates were similar for the two groups. For the elongated group, the target-present error rate was 7.0%, and the target-absent value was 4.2%. For the unoriented group, the rates were 8.1% and 6.1%.

The results support the hypothesis that the processes involved in detecting the target were altered by using elongated objects for half of the distractors. Inclusion of slow-moving, elongated distractors prevented the fast target from popping out. Note that the addition of objects with a high width:height ratio was not in itself sufficient to produce the effect. Reaction times were minimally affected by display size in the pilot experiment with stationary elongated objects. It appears that the objects must move to create the spatiotemporal representations.

Nonetheless, there are differences between the results of Experiment 5 and the results obtained for the slow target conditions of Experiments 1–4, which indicate that the temporal filter hypothesis will not provide a complete explanation of the search asymmetry. First, the time to detect the presence of a target was negligibly affected by display size for 2 of the 11 subjects in the elongated group, suggesting that these

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[3] The slopes may be underestimated because they are calculated over all of the display items, whereas only half of the distractors were elongated. It is possible that the distractors with a low width:height ratio were ignored.

subjects were able to process the displays in parallel. Second, the results of the individual regression analyses were inconsistent. On the target-present trials, the proportion of variance accounted for by a linear component exceeded 75% for only 4 of the 11 subjects in the elongated group. The figure for target-absent trials was 8 of 11. Thus, the current manipulation of width:height ratio does not produce functions comparable to those obtained when searching for a slow target among fast distractors.

We have conducted a replication of this experiment to test these conclusions further. There were two methodological changes in the replication. First, we reversed the luminances assigned to the target and background so that the displays consisted of black objects on a white background.[4] Second, we used a within-subjects design by testing subjects in separate blocks on the displays with the elongated and unoriented distractors.

The mean reaction times on target-present trials for the elongated blocks were 1,064, 1,145, 1,186, and 1,448 ms for array sizes of 3, 7, 11, and 15. The means for the unoriented blocks were 1,123, 1,191, 1,138, and 1,263 ms. Reaction times for the unoriented displays were not faster than for the elongated displays. We are unable to account for the discrepancy between these data and those shown in Figure 5. In other respects, however, the data are similar to the results shown in Figure 5. As display size increased, reaction time increased more rapidly when the display contained elongated distractors than when it contained unoriented distractors. On target-present trials, the mean slope was 28 ms for the elongated blocks and 9 ms for the unoriented blocks. Although the Distractor Type × Display Size interaction was not significant, $F(3, 39) = 1.43$, the slope was larger for the elongated trials for 12 of the 14 subjects and equal for 1 of the other 2 subjects. Thus, the elongated distractors tended to produce greater interference on the search process than the unoriented distractors.

More important, however, the results of this replication support the conclusion that the temporal filtering hypothesis does not provide a complete account of the speed asymmetry. The time to detect a slow target among fast distractors conformed to a linear function for almost all subjects in the preceding experiments. In contrast, a linear component accounted for more than 75% of the variance for only 6 of the 14 subjects in the present experiment for displays containing a fast target among slow, elongated distractors.

General Discussion

Direction of motion appears to be an elementary feature of visual perception in the same manner as orientation and color (Dick et al., 1987; Ivry & Cohen, 1990; Nakayama & Silverman, 1986). The current experiments were designed to investigate the second component of motion, speed. We used the visual search paradigm to determine whether differences in movement speed would be rapidly detected or whether such discriminations require a limited-capacity attentional process.

In the first four experiments, we observed an asymmetry in search tasks involving manipulations of speed. Subjects were more adept at detecting a fast target among slow distractors

than the reverse. When the target speed was twice the distractor speed, reaction time to detect the presence of a fast target was relatively independent of the number of distractors in the display. When a slow target was searched for among fast distractors, however, the search functions reflected an attention-demanding process. This asymmetry appears robust across the range of speeds tested.

The asymmetry argues against a model of speed perception that was derived to parallel the simplest model proposed by Treisman and associates to account for search of features such as color and orientation. The Treisman model (e.g., Treisman & Gormican, 1988, p. 17) postulates sets of detectors, with each set tuned to different values along a given stimulus dimension. Each set, or feature map, is composed of similarly tuned detectors spanning different regions of the visual field. For example, the dimension of color may be represented by feature maps for red, green, blue, and so forth. An analogous model for speed would postulate feature maps of motion detectors, with each map tuned to a limited range of speeds. Responses in visual search would be based on the presence or absence of activity in the relevant set of speed detectors. This model cannot account for the asymmetry. There is no provision for why it should be easier to examine the activity level in fast detectors than in slow detectors. A recent alternative account of the data from visual search tasks (Duncan & Humphreys, 1989) is not able to provide a parsimonious account for the speed asymmetry or other asymmetries.

We explored three hypotheses that might account for the asymmetry. First, according to some models of motion perception, speed perception is based on the outputs of detectors sensitive to temporal frequency rather than speed per se (Sekuler et al., 1978; Smith, 1987; Tolhurst et al., 1973). The visual search asymmetry cannot be attributed to differences in temporal frequency, however. When the temporal frequency of the fast and slow objects was either equated or varied randomly, an advantage favoring fast targets was still obtained (Experiment 3). Second, visual search asymmetries have been accounted for by assuming that there is a quantitative difference in the output of a single set of detectors when these detectors are activated by displays with either the preferred or the nonpreferred target (Treisman & Gormican, 1988). The asymmetry reflects the fact that one pairing of the two stimuli to target and distractor is more discriminable than the reverse pairing. The asymmetry in speed did not disappear when discrimination was held constant over two ranges of speeds (Experiment 4).

Third, we considered whether the asymmetry reflects differences in the representations of motion information after

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[4] By reversing contrast, we can rule out potential artifacts due to phosphor persistence. Additionally, we measured phosphor persistence of the white-on-black displays by examining the output of a light-detecting device on an oscilliscope. The phosphor energy had fallen below 10% in about 4 ms. As pointed out by one of the reviewers, however, human sensitivity is much finer than standard light-detecting devices. Thus, the reverse-contrast experiment provides a stronger argument that the proposed spatiotemporal filtering process is psychological and not a monitor artifact. We thank Dave Irwin for stressing the importance of this issue.

spatiotemporal filtering (see Adelson & Bergen, 1985). Spatiotemporal blurring of unoriented moving objects would create representations that were oriented along the direction of motion. Such a process was proposed to account for the finding that a target moving horizontally popped out from an array of distractors moving vertically (Ivry & Cohen, 1990). Spatiotemporal filtering produces a representation in which the target is oriented horizontally among vertically oriented distractors. In the current experiments, all of the objects oscillated horizontally; thus, there would not be a difference in terms of the direction of orientation created after spatiotemporal filtering. Assuming the same temporal integration operators for fast and slow objects, however, a spatiotemporal blurring mechanism would create more elongated representations along the direction of motion for fast objects in comparison to slow objects. It was thus proposed that the more elongated representations of fast objects might be easier to detect than the less elongated representations of short objects. This asymmetry has been found in static displays in which line length was manipulated (Beck, 1974; Treisman & Gormican, 1988).

A test of this account provided mixed results (Experiment 5). Inclusion of slow-moving, elongated distractors generally prevented a fast, unoriented target from popping out. Reaction time, however, was relatively independent of display size for some subjects, and the regression analyses indicated that the search functions were quite different from those obtained in the slow target conditions. Moreover, the speed asymmetry cannot be completely explained by analogy to the line-length asymmetry reported by Treisman and Gormican (1988). They found that the line-length asymmetry disappeared when discrimination was held constant; the speed asymmetry persisted under a similar manipulation in Experiment 4.

Each of the hypotheses considered to this point entails certain assumptions about the properties of motion detectors. The simple feature-map model assumes that a given detector is sensitive to a limited range of speeds. That is, there is a collection of heterogeneous detectors with limited overlap. The other hypotheses generally assume a single set of more or less homogeneous detectors. Asymmetries arise because of quantitative differences in the output of these detectors, because of differences in either temporal frequency or discrimination.

An alternative account of the asymmetry can be developed by considering other structural possibilities for speed detectors. Specifically, consider an array of speed detectors, each tuned to respond to objects moving at some minimum speed and all faster speeds: in other words, detectors that act as high-pass filters. A set of hypothetical detectors is depicted in Figure 6. Unit B is sensitive to speeds 5°/s and faster. Unit A responds to all of the stimuli that drive Unit B but is also sensitive to speeds as low as 2°/s.

This model would produce the asymmetry observed in the current experiments. For example, in Experiment 2, the fast objects moved at 6.4°/s, and the speed of the slow objects was 3.2°/s. First, consider search for a fast target among slow distractors. When the target is absent, only those detectors with a low-speed cutoff below 3.2°/s will respond (e.g., Unit A). The target will activate these same units, but it will also
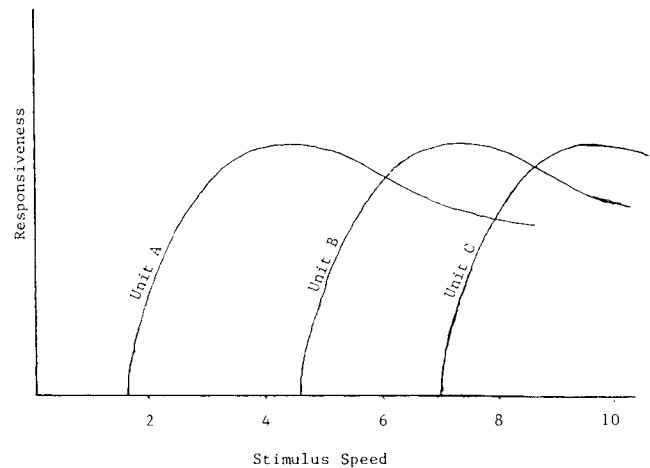

Figure 6. Set of hypothetical detectors for speed perception. The high-pass property of the detectors would produce the search asymmetry.

activate units with higher cutoff points (e.g., Unit B). Thus, the target can be detected by the presence of activity in these latter units. Now consider search for a slow target among fast distractors. Because of the high-pass properties of the detectors, the fast distractors will activate all of the detectors with a low cutoff below their speed (e.g., Units A and B). The inclusion of a slow-moving object on target-present trials does not lead to activation of any new detectors. Thus, the model predicts an asymmetry favoring fast targets because in this condition target-absent and target-present trials involve the activation of nonidentical detectors.

The model outlined in Figure 6 is a variant of an account of search asymmetries discussed by Treisman and Gormican (1988, p. 32).[5] They argued that asymmetries may arise when there are differences in the bandwidth of overlapping pairs of detectors. Specifically, search will be slow when the distractors fall within the region of overlap because both detectors will be activated. When the target is within the region of overlap and the distractors are outside this region, however, search should be easy because the target will activate a unique detector. The Treisman and Gormican (1988) model, developed to account for differences between search for prototypical and nonprototypical targets, assumed symmetric detectors. The current band-pass proposal can be considered a generalization of this model.

Converging evidence for modeling speed detectors as high-pass filters can be found in the literature. The strongest evidence comes from research on motion adaptation. In adaptation experiments, sensitivity to a test stimulus is decreased after prolonged exposure to an adapting stimulus. The adaptation effect is assumed to occur because detectors that respond to both the adapting and test stimuli are desensitized during the adapting period. From Figure 6, a prediction can be derived in which speed adaptation effects are expected to

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[5] We are indebted to Anne Treisman for helping develop the current generalization of her previous account of search asymmetry.

be asymmetrical (see also Smith, 1985). Assume that the speed of the adapting stimulus is slow and that the test stimulus is fast. Detectors with a low cutoff above the speed of the adapting stimulus will not be desensitized. In contrast, when the speed of the adapting stimulus is faster than the test stimulus, adaptation should be much more marked. This is predicted because the fast adapter will activate the same detectors that respond to the slow test stimulus. In summary, adaptation with fast stimuli is predicted to be much more effective than adaptation with slow stimuli.

The predicted asymmetry has been reported in numerous psychophysical experiments (Hunzelmann & Spillman, 1984; Smith, 1985, 1987; Thompson, 1981, 1983). Thompson (1981) found that the perceived speed of a test object was reduced when preceded by an object that moved at a faster speed. When the adapting stimulus moved at a slower speed than the target, the adaptation effect was either reduced or negligible. Smith (1985) provided a replication of this asymmetry, systematically manipulating the speed of the adapting and test stimuli. In one set of conditions, the test velocity of a drifting grating was held constant at 4°/s. When the velocity of the adapting stimulus was 1° or 2°/s, the perceived velocity of the test grating was veridical. When the speed of the adapting stimulus was 4°/s or faster, the speed of the test grating was judged to be slower. The adaptation effect was greatest when the speed of the adapting stimulus was 8°/s and did not increase for faster adapters. In a latter study, Smith (1987) reported that for a 5°/s test stimulus, the adaptation effect was similar for adapting speeds between 10°/s-25°s, becoming weaker with speeds below or above this range.

It is of interest to note that as in the visual search asymmetry, temporal frequency information is not the critical variable underlying the adaptation effect (Smith, 1985; Thompson, 1981). Smith (1985) reported similar asymmetrical adaptation functions occurring for periodic stimuli with different spatial frequencies as well as occurring after exposure to aperiodic stimuli (i.e., stimuli without a fixed temporal frequency). Moreover, adaptation can occur with stationary flickering stimuli, but the effect is much weaker than that observed with moving stimuli (Smith, 1985; see also Schieting & Spillman, 1987).

Physiological evidence for the model outlined in Figure 6 can be found in the literature. Hammond, Mouat, and Smith (1988) recorded from cells in Area V1 of a cat during an adaptation experiment. In accord with the psychophysical results, reduction in cell response to a stimulus of a fixed speed was much lower after prolonged exposure to stimuli moving at faster speeds. A more direct assessment of the hypothesis that speed detectors operate as high-pass filters can be made by examining the velocity-tuning curves of cells responding to moving stimuli. Recordings made in the middle temporal cortex of owls and macaque monkeys are supportive of the hypothesis that motion detectors are high-pass filters for speed (Allman et al., 1985; Maunsell & Van Essen, 1983).[6]

Results from two disparate paradigms suggest that speed perception is derived from the output of detectors that operate as high-pass filters in the velocity domain. These detectors would yield the visual search asymmetry reported in the current study as well as the asymmetrical adaptation effects.

It is likely that these detectors do not respond to the speed of a stimulus independently of all other stimulus variables. Spatial and temporal manipulations are likely to have an effect, as evidenced by the increase in intercept when temporal frequency was randomized in Experiment 3 and the interference created by including elongated distractors in Experiment 5 (see also Burr, Ross, & Morrone, 1986; Dawson & Di Lollo, 1990). A challenge for future experimentation is to differentiate the primary and secondary variables for motion perception.

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[6] Most of the speed-tuning curves shown in Maunsell and Van Essen (1985) appear to be symmetric. Speed, however, is plotted on the abscissa on logarithmic coordinates (see Allman, Miezen, & McGuinness, 1985). If the data are replotted on linear coordinates, the functions resemble high-pass filters. Of course, it is a psychological question whether the appropriate coordinates are linear or logarithmic. Data from psychophysical experiments with humans suggest linear coordinates because Weber's law is observed in velocity-discrimination tasks (McKee, 1981; Smith, 1987). Nevertheless, there are differences in species as well as differences in the range of speeds tested between these psychophysical experiments and the single-cell studies.

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1993 APA Convention "Call for Programs"

The "Call for Programs" for the 1993 APA annual convention appears in the October issue of the APA Monitor. The 1993 convention will be held in Toronto, Ontario, Canada, from August 20 through August 24. Deadline for submission of program and presentation proposals is December 10, 1992. Additional copies of the "Call" are available from the APA Convention Office, effective in October. As a reminder, agreement to participate in the APA convention is now presumed to convey permission for the presentation to be audiotaped if selected for taping. Any speaker or participant who does not wish his or her presentation to be audiotaped must notify the person submitting the program either at the time the invitation is extended or prior to the December 10 deadline for proposal submission.