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Velocity dependence of Vernier and letter acuity for band-pass filtered moving stimuli

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Abstract

The ability to see fine detail diminishes when the target of interest moves at a speed greater than a few deg/s. The purpose of this study was to identify fundamental limitations on spatial acuity that result from image motion. Discrimination of Vernier offset was measured for a pair of vertical abutting lines and letter resolution was measured using a four-orientation letter 'T'. These stimuli were digitally filtered using one of five band-pass (bandwidth = 1.5 octaves) filters with a center frequency between 0.83 and 13.2 c/deg, and presented at velocities that ranged from 0 to 12 deg/s. Filtered and unfiltered stimuli were presented for 150 ms at a constant multiple (4× or 2×) of the contrast-detection threshold at each velocity. For stimuli of low to middle spatial frequency (up to 3.3 c/deg), Vernier and letter acuity for equally detectable targets are essentially unaffected by velocity up to 12 deg/s, i.e., for temporal frequencies of motion (velocity × spatial frequency) up to approximately 50 Hz. For stimuli of higher spatial frequency, acuity remains essentially constant until the velocity corresponds to a temporal frequency of about 30 Hz, and increases thereafter. Both Vernier and letter acuities worsen by approximately a factor of two for each one-octave decrease in filter spatial frequency. Both types of acuities worsen also as the contrast of the stimulus is reduced, but Vernier discrimination exhibits a stronger contrast-dependence than letter resolution. Our results support previous suggestions that a shift in the spatial scale used by the visual system to analyze spatial stimuli is principally responsible for the degradation of acuity in the presence of image motion. The results are consistent with a spatio-temporal-frequency limitation on spatial thresholds for moving stimuli, and *not* with a temporal-frequency limitation per se.

Keywords: Vernier acuity; Letter acuity; Motion; Spatial frequency; Temporal frequency

1. Introduction

The ability to see fine spatial detail is exquisite when the object of interest is stationary, and diminishes in the presence of image motion (e.g., Brown, 1972; Westheimer & McKee, 1975). Under optimal conditions of high stimulus contrast and luminance, spatial thresholds such as Vernier and resolution acuities are degraded only by image motion faster than 2–3 deg/s (Barnes & Smith, 1981; Brown, 1972; Henderson, Halmagyi, & Curthoys, 1986; Morgan, Watt, & McKee, 1983; Westheimer & McKee, 1975). Previously, we demonstrated that the elevation of spatial thresholds for moving broad-band and low-pass filtered stimuli is consistent with a shift in visual sensitivity toward lower spatial frequency mechanisms (Chung & Bedell, 1998; Chung, Levi, & Bedell, 1996). These results imply that spatial thresholds are elevated during motion primarily because larger (lower frequency) spatial filters are used to analyze the moving objects, and not solely because of a reduction in target visibility due to motion smear. An interesting, and perhaps counter-intuitive, prediction based on this shift-in-spatial-scale hypothesis is that spatial thresholds should be unaffected by the velocity of a moving target if the same spatial frequency mechanism is used to analyze the target regardless of velocity. Spatial thresholds that are independent of target velocity have not been reported previously.

We attribute the lack of threshold-constancy in our previous studies to the use of broad-band or low-pass filtered stimuli. Because a range of spatial frequency information is present in these stimuli, the visual system

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was afforded the opportunity to use progressively lower spatial frequency mechanisms to analyze these targets as the velocity of image motion increased. The purpose of this study was to use band-limited stimuli to restrict the spatial frequency content of the targets, thus allowing us to directly test the shift-in-spatial-scale hypothesis in explaining the threshold elevation for moving stimuli.

According to the shift-in-spatial-scale hypothesis, two predictions can be made. First, thresholds for spatial tasks should be independent of velocity, for band-limited stimuli that carry only a relatively narrow range of spatial frequency information. Second, thresholds should be inversely proportional to the spatial frequency of the stimuli. In other words, for a twofold increase in stimulus spatial frequency, thresholds should decrease by a factor of two. This second prediction is based on the notion that the precision of performing a spatial task depends on the inherent uncertainty of the most sensitive spatial frequency mechanism, which is represented by the width and/or the slope of the spatial-tuning function of that mechanism (Krauskopf & Farell, 1991; Levi & Waugh, 1994; Levi, Waugh, & Beard, 1994; Morgan & Aiba, 1985). Note that two caveats should be kept in mind for these predictions: (1) we are only considering targets that are equally visible, as spatial acuity varies with target visibility; and (2) we are only considering tasks that are commonly believed to be mediated by the contrast response of single spatial frequency mechanisms or the differential contrast responses from a range of spatial frequency mechanisms tuned to different spatial frequencies or orientations. An example is the discrimination of offset in a pair of abutting Vernier targets. Tasks that are mediated by spatial frequency mechanisms are usually highly contrast-dependent and are very sensitive to the effect of blur. In contrast, discrimination of offset in a pair of separated Vernier targets is believed to be mediated by a position, or local sign mechanism (Burbeck, 1987; Toet, Eekhout, Simons, & Koenderink, 1987). Such tasks usually show little contrast-dependence and are resistant to the effect of blur. Based on the properties of the spatio-temporal contrast sensitivity function, the spatial thresholds for moving stimuli should be subject to a temporal-frequency limitation as well. What is unclear is whether the visual system is subjected to a *fixed* temporal-frequency limit, as suggested by previous reports (i.e., 30 Hz as reported by Morgan & Castet, 1995; or 10 Hz as reported by Levi, 1996), or whether the temporal-frequency limitation depends on the spatial properties of the stimulus for a specific spatial task. To anticipate, we found that similar temporal-frequency limitations exist for Vernier and letter acuity. The "temporal-frequency limit" does not depend on the task, but it does depend on the spatial frequency content of the stimuli, implying a *spatio-temporal-frequency* limitation, instead of a temporal-frequency limitation per se.

2. General methods

We measured thresholds for Vernier discrimination with pairs of abutting lines and letter resolution with single letters 'T'. All targets were spatially filtered using two-dimensional, circularly symmetric exponential band-pass filters with *object* center-frequencies (i.e., independent of viewing distance) of 4, 8, and 16 c/screen. Samples of the filtered Vernier lines and letters T are given in Fig. 1. When combined with our three viewing distances of 2, 4, and 8 m, we obtained targets with *retinal* center-frequencies of 0.83, 1.65, 3.3, 6.6 and 13.2 c/deg (Table 1). In this paper, when we refer to the spatial frequency of a stimulus, we are in fact referring to the center frequency of the stimuli. Bandwidth of the filters, expressed as the full-width at half-height, was 1.5 octaves. Filtering was carried out with the HIPS software (Landy, Cohen, & Sperling, 1984). Each filter was calibrated by providing sine-wave stimuli of known spatial frequencies and an amplitude of 1 as the input, and measuring the output of the signals after filtering. Fig. 2 plots the amplitudes of the output sine-waves after filtering in the form of modulation transfer functions.

To create a digitally filtered image, each stimulus was first centered on a "screen" of 256×256 pixels with each pixel assigned a luminance value of either 0 (black for background) or 254 (white for stimulus). These stimuli were then Fourier transformed and multiplied by one of the three band-pass filters, rendered in the frequency domain. An inverse Fourier transform was then performed on the product, which resulted in the final filtered image. After filtering, the luminance values of the filtered images fell within the range of ± 127. Owing to the relatively small stimulus sizes that we used and the need to present stimuli efficiently, we cropped the final filtered images to the central 128×128 pixels for the stimuli used to assess letter resolution, and to the central 80×200 pixels of the filtered Vernier stimuli. Image cropping did not remove any significant luminance modulation that was present in the original filtered images.

The filtered targets were stored as digital images and were presented at 240 Hz on a monochrome monitor (Image Systems, Hopkins, MN) using the frame-store capability of a Visual Stimulus Generator computer board and software (VSG 2/3, Cambridge Research Systems, UK). The monochrome monitor was equipped with an ultra-fast decay phosphor, DP104, which has a peak luminance output at about 565 nm and a spectral bandwidth of about 90 nm. The luminance of an intensified spot diminishes to $<1\%$ in about 250 μs. At 2 m, each pixel on the monitor screen subtended a square of 68×68 arc s and the entire screen subtended 10.3×7.7 deg. When read into the program during the experiment, the luminance value of each pixel was first

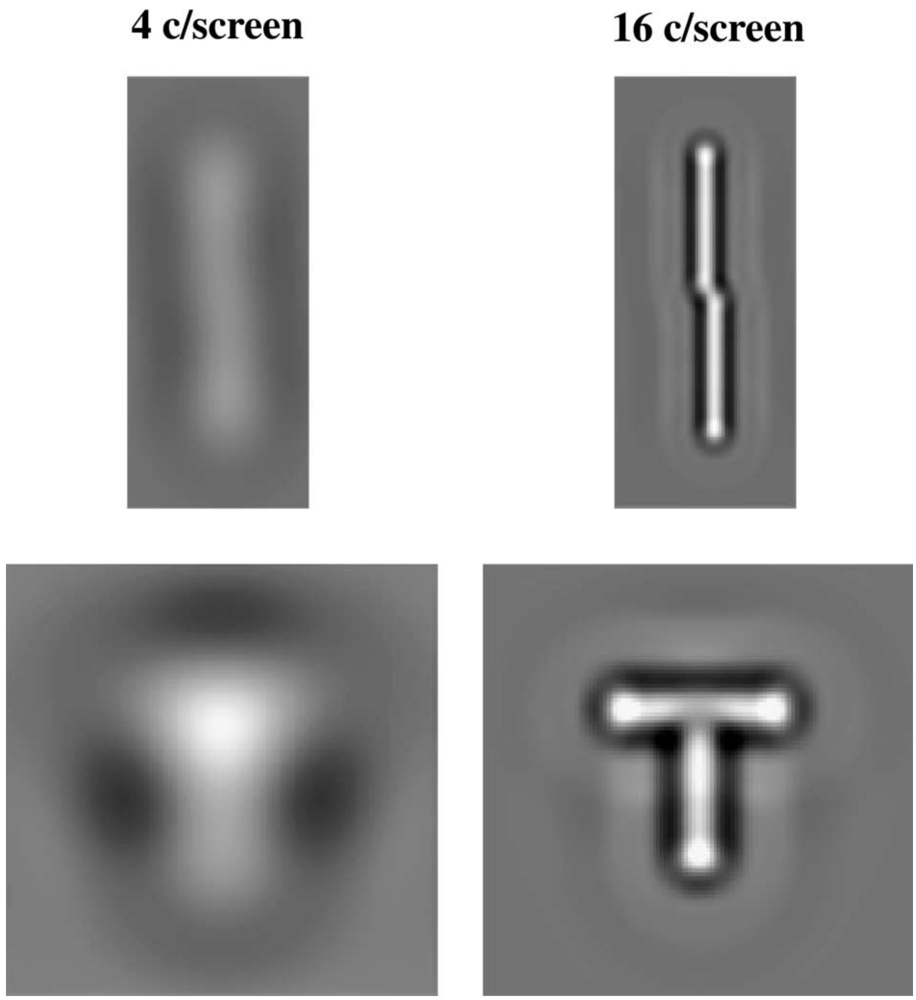

Fig. 1. Samples of band-pass filtered Vernier (top row) and letter T (bottom row) stimuli. The two filtered Vernier stimuli were obtained by applying a 4 c/screen (left) and a 16 c/screen (right) filter to the same unfiltered Vernier stimulus. Similarly, the two filtered letter Ts were obtained by applying the same filters to an unfiltered letter T.

Table 1
Conversion between object (c/screen) and retinal (c/deg) spatial frequencies for the band-pass filters used in the study

Viewing distance (m)	Object spatial frequencies (c/screen)		
	4 (c/deg^{V,T})	8 (c/deg^{V})	16 (c/deg)
2	0.83	1.65	3.3^{T}
4	1.65	3.3	6.6^{T}
8	3.3	6.6	13.2^{V,T}

Superscript letters 'V' and T indicate the retinal spatial frequency filters used in Vernier discrimination and letter resolution, respectively.

modulated by the contrast level required of the stimulus, after which a value of 127 was added uniformly to all pixels to shift the mean luminance of the stimulus to that of the screen (50 cd/m^2). An exact mapping of luminance values was accomplished by photometrically pre-calibrating the monitor using the OPTICAL attachment and VSG software (Cambridge Research Systems, UK). At the 4 and 8 m viewing distances, the monitor screen was viewed with a surrounding cardboard mask, flood-lit by two lamps through combinations of gelatin filters (Edmund Scientific, Barrington, NJ) to closely match the luminance and color of the monitor. Because the mask was located closer to the observer than the monitor, virtually none of the illumination from the two flood lamps reached the face of the monitor. At the 4 and 8 m-viewing distances, the cardboard mask subtended 12.8 × 10.8 deg and 6.4 × 5.4 deg, respectively.

Image motion was produced by viewing the target and the surrounding mask (at 4 and 8 m) from a front-surface mirror, mounted on a galvanometer (General Scanning G300, Watertown, MA) that was driven by a ramp wave form. The ramp wave form was generated by a programmable function generator (Hewlett Packard 3318A) that was, in turn, controlled by a personal computer via an IEEE interface card (B & C Microsystems, Sunnyvale, CA). For each velocity that we examined (0, 2, 4, 8 and 12 deg/s), the function generator generated an amplitude for the ramp wave form that was appropriate for the desired velocity. Calibration of

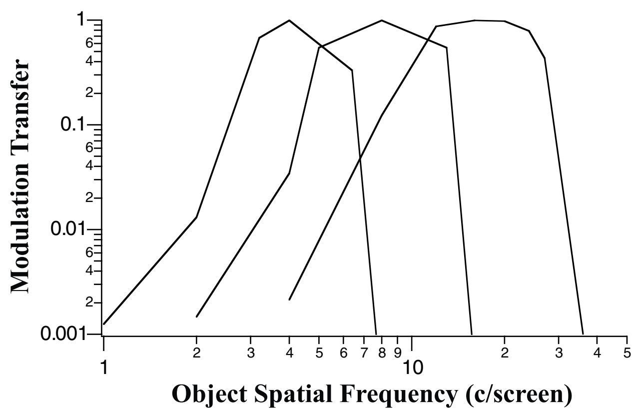

Fig. 2. Modulation transfer functions of the band-pass filters used in this study. The output amplitude of a sine-wave grating after filtering is normalized to the input amplitude and plotted as a function of spatial frequency. The object center frequency of these filters are, from left to right, 4, 8 and 16 c/screen, respectively. When specified in terms of retinal spatial frequencies, the center-frequency of these filters correspond to 0.83, 1.65, 3.3, 6.6 and 13.2 c/deg (see Table 1), for the three viewing distances used in this study.

the amplitude of mirror movement was performed prior to the commencement of data collection and re-checked at regular intervals during the course of the study. On each trial, the observer first viewed a stationary black fixation square ($\approx 0.2 \times 0.2$ deg at 8 m, and $\approx 0.4 \times 0.4$ deg at 4 and 2 m). When ready, the observer pressed the fire-button on a joystick to initiate a trial. Following a blank period of 250 ms, the stimulus was presented on the monitor for 150 ms during which the mirror was deflected to produce image motion. The observer was required to indicate his/her response by pushing the joystick in the appropriate direction, after the mirror ceased its movement. The stimulus duration, as well as the random presentation of leftward and rightward target motion, were chosen to minimize pursuit eye movements. Testing was monocular using the right eye and the natural pupil, with the non-viewing left eye occluded.

Three observers, one of the authors and two observers unaware of the purpose of the study, participated in the experiments. All have (corrected) vision of 20/20 or better and participated in our earlier study with low-pass filtered moving stimuli (Chung & Bedell, 1998). Thus, they were all experienced in viewing moving stimuli and were well practiced with the psychophysical paradigms used to collect data in this study. Each observer voluntarily granted written informed consent after the procedures of the present experiments were explained, and before the commencement of data collection. Although described in sequence here, the experiments on Vernier discrimination and letter resolution were conducted in parallel in an interleaved order. The sequence of testing the various target spatial frequencies and velocities was randomized within and between observers.

Each datum reported in this paper represents the value averaged across 4–6 blocks of trials, weighted by the inverse variance of each threshold estimate (Klein, 1992). Curve-fitting was accomplished using Igor Pro™, which utilizes a Levenberg-Marquardt iterative algorithm to minimize the error between the experimental data and the model fit. Except when specified, the experimental data were weighted by the inverse of the standard error of the mean value of each threshold estimate during curve-fitting.

3. Experiment 1: Vernier discrimination

3.1. Methods

Vernier thresholds were measured for unfiltered and band-pass filtered vertical abutting line stimuli, as a function of stimulus velocity up to 12 deg/s. The use of line Vernier stimuli instead of Gabor patches or sine-wave gratings, which are also band-limited in nature, allows us to compare the results with those of our previous studies (Chung & Bedell, 1998; Chung et al., 1996) in which line Vernier stimuli were used. The dimensions of each line in the unfiltered stimulus were 1.14×18.2 arc min, equivalent to 1×16, 2×32, and 4×64 pixels at viewing distances of 2, 4, and 8 m, respectively. To ascertain that our results are independent of the actual field size of the stimulus, we tested two conditions twice (viz, 1.65 and 3.3 c/deg), using different combinations of object spatial frequency filter and viewing distance.

To avoid the confounding effect of target visibility on Vernier thresholds, we used stimuli that were equally visible in the presence of image motion. To do so, we first measured the detection threshold for a single line which was identical to one of the lines that made up the Vernier stimulus. Detection thresholds for an unfiltered line stimulus, and the various filtered stimuli used in the study were determined for each of the five velocities, using a staircase procedure described by Bedell, Chung, and Patel (2000) and Chung and Bedell (1998). On each trial, the line stimulus was presented in one of two temporal intervals, each denoted by an audio-tone. The task of the observer was to indicate in which interval the stimulus was presented. No feedback was provided. The staircase decision rule tracked a detection threshold corresponding to a 75% observed correct probability on the psychometric function. Six reversals were determined for each staircase and the average of the last four reversals represents the detection threshold for that block of trials. For each testing condition, four to five independent estimates of the detection threshold were averaged and the mean was taken as the value to which the visibility of the Vernier stimuli were normalized.

Unfiltered stimuli and band-pass filtered stimuli of 0.83–6.6 c/deg were presented at 4× their individual contrast-detection thresholds (abbreviated as contrast-threshold units, or CTU). Stimuli filtered with the 13.2 c/deg filter were presented at 2× CTU, due to their high contrast-detection thresholds. Vernier thresholds were measured also for filtered stimuli of 6.6 c/deg at 2× CTU. Presumably, the use of stimuli of relatively low visibility helped to force the visual system to use the same band of spatial frequency mechanisms to detect, as well as analyze the stimuli. When stimulus visibility is high, there is a chance that spatial frequencies other than the center frequency of the band-pass filters (i.e., off-frequency) would contain enough energy to perform the task.

Vernier thresholds were measured using the same procedures as in our previous studies (Bedell et al., 2000; Chung & Bedell, 1998). In brief, we presented the stimuli using the method of constant stimuli where, within each block of 70 trials, the upper test line was presented randomly at one of seven offset positions: 1, 2, or 3 units to the right or left of the lower reference line, or aligned with it. The observer's task was to discriminate in which direction the upper test line was shifted with respect to the lower reference line. Audio feedback was given to indicate whether the observer's response was correct or not. Responses to the "right" were tallied for each block of trials and were analyzed later using probit analysis. Vernier threshold was defined as the Vernier offset required to increase the rightward responses on the psychometric function from 50% to 84%. This definition of threshold is equivalent to one standard deviation of the cumulative Gaussian function that is fit to the observer's responses.

3.2. Results

Vernier thresholds for unfiltered and filtered stimuli with spatial frequencies up to 6.6 c/deg are plotted for the three observers as a function of stimulus velocity in Fig. 3a, for a stimulus contrast of 4× CTU. Two sets of data are presented for 1.65 and 3.3 c/deg stimuli, using two different combinations of object spatial frequency and viewing distance. The similarity between the pairs of datum points for the same retinal spatial frequency indicates that thresholds depend on the retinal spatial frequencies contained in the stimulus and not the field size or the object spatial frequency of the stimulus.

Fig. 3b presents the results for filtered stimuli of spatial frequencies 6.6 and 13.2 c/deg, obtained at 2× CTU. For comparison, data for unfiltered and filtered stimuli of 6.6 c/deg at 4× CTU are replotted from Fig. 3a. For 13.2 c/deg filtered stimuli, Vernier thresholds worsen with image motion beyond 1–2 deg/s.

These results are qualitatively consistent with both predictions of the shift-in-spatial-scale hypothesis. First, Vernier thresholds for band-pass filtered stimuli remain virtually constant across the range of velocities tested, for target spatial frequencies of 3.3 c/deg or lower. However, for 6.6 c/deg filtered stimuli, Vernier thresholds remain constant only up to about 4 deg/s, and increase at higher velocities. In comparison, and as in previous studies, Vernier thresholds for the unfiltered stimuli increase with image velocity beyond 1–2 deg/s. Second, Vernier thresholds for filtered stimuli change by approximately a factor of two for each one-octave change in stimulus spatial frequency, except for a spatial frequency of 0.83 c/deg. This departure from the predicted change in threshold at this lowest spatial frequency will be discussed below.

To evaluate quantitatively whether Vernier thresholds obtained at low spatial frequencies are indeed constant across the range of velocities tested, we fit each set of threshold vs. velocity data with a straight line with a slope of zero, and compared the goodness-of-fit with a two-line fit in which the slope of the first line was constrained to zero and the slope of the second line was free to vary. Because of the logarithmic y-axis, the second fitted line appears as an exponential curve, instead of a straight line in the figures. The better fit to each data set, as defined by the one that yields the smaller value of Chi-square after correction for the number of fitted parameters, is shown in Fig. 3. If velocity has no effect on Vernier thresholds, then a single line with a slope of zero should provide a better fit. On the contrary, if Vernier thresholds tolerate motion only up to a certain velocity, then the two-line fit should be better, with the intersection of the two-lines representing the velocity at which threshold-constancy breaks down. In general, the data for filtered stimuli up to and including 3.3 c/deg are better fit by single straight lines with a slope of zero, implying that thresholds for these band-pass filtered stimuli are unaffected by image motion once they are equated for visibility, at least for the range of velocities examined. For unfiltered and filtered stimuli of 6.6 and 13.2 c/deg, the data are better represented by the two-line fit.

We also evaluated quantitatively whether or not the change in Vernier thresholds follows the factor-of-two prediction. To do so, we fit a power function to the thresholds shown in Fig. 3a for 4×-CTU stimuli as a function of spatial frequency. For the 6.6 c/deg stimuli, we used the thresholds obtained at low velocities, before thresholds began to be degraded by velocity. For the 0.83 c/deg stimuli, we used the thresholds obtained using longer Vernier lines (see below). An exponent of -1 implies that each one-octave change in spatial frequency yields a factor-of-two change in Vernier threshold. The exponent of the power function we obtained is -0.83 ± 0.07, a value that is close to -1.

As mentioned above, there was a departure from the predicted change in threshold at 0.83 c/deg. We speculated that this departure might be attributable to the use

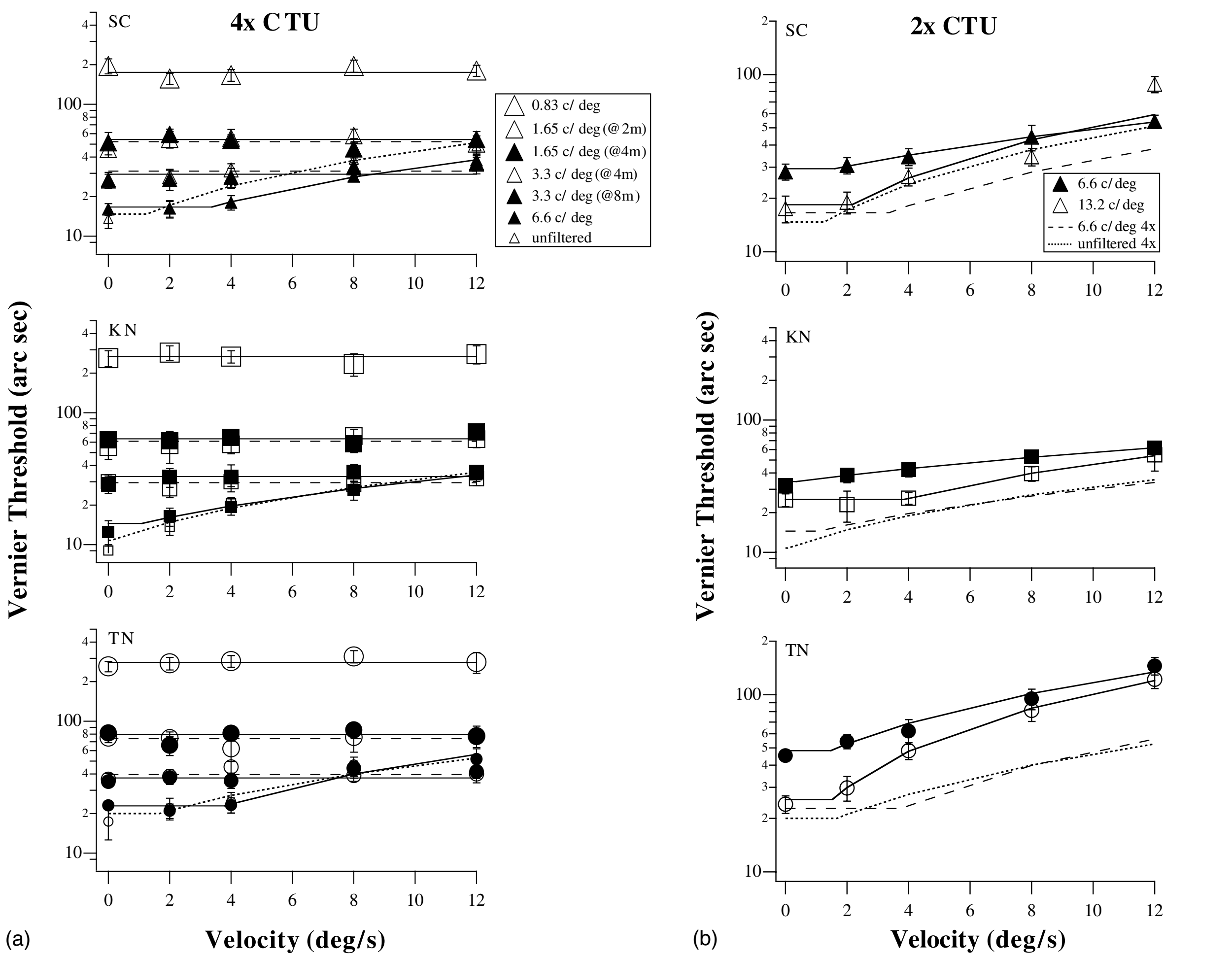

Fig. 3. (a) Vernier threshold (arc s) is plotted as a function of stimulus velocity (deg/s) for unfiltered and filtered stimuli of spatial frequencies 0.83–6.6 c/deg. The stimuli were all presented at 4× CTU. Note that thresholds were measured twice for filtered spatial frequencies of 1.65 and 3.3 c/deg, with different combinations of filter object frequency and viewing distance. Lines drawn are either a single-line fit with a slope fixed at zero, or a two-line fit with the slope of the first line constrained to zero and that of the second one free to vary. Lines of non-zero slope appear as exponential curves because the data are plotted on logarithmic y-axes. Error bars represent ±1 s.e.m. and are smaller than the size of the symbols when not shown. (b) Vernier threshold (arc s) is plotted as a function of stimulus velocity (deg/s) for filtered stimuli of spatial frequencies 6.6 and 13.2 c/deg (lines with symbols). The stimuli were presented at 2× CTU. For comparison, results obtained for unfiltered and filtered stimuli of 6.6 c/deg presented at 4× CTU are also plotted (dotted and dashed lines, respectively). Solid lines represent the best fitting two-line fits.

of stimuli that were too small (line-length = 18.2 arc min) compared with the receptive field of a 0.83 c/deg mechanism, thus denying the mechanism the opportunity for complete spatial integration. To test this speculation, we measured Vernier thresholds for 0.83 c/deg stimuli using a line-length that was four times longer (72.8 arc min) than the original stimulus, a length that is clearly longer than one half-period of a 0.83 c/deg mechanism. For comparison, Vernier thresholds were measured also for 1.65 c/deg stimuli using these longer line stimuli. The results are summarized in Table 2. Using the 72-arc-min lines, Vernier thresholds for 0.83 c/deg stimuli decrease to approximately half the value for the original 18-arc-min lines, whereas thresholds for 1.65 c/deg stimuli improve minimally. The twofold improvement in Vernier thresholds with 0.83 c/deg filtered

Table 2
Vernier thresholds (arc s) obtained using line-lengths of 18.2 and 72.8 min for 0.83 and 1.65 c/deg stimuli

	18.2-min line	72.8-min line
0.83 c/deg		
0 deg/s	239.4 ± 27.2	107.7 ± 12.1
12 deg/s	247.0 ± 40.5	119.5 ± 17.7
1.65 c/deg		
0 deg/s	61.9 ± 6.5	53.1 ± 7.5
12 deg/s	65.7 ± 7.0	58.1 ± 10.4

Stimulus velocity was either 0 (stationary) or 12 deg/s. Thresholds given are the values averaged across the three observers. Error bars represent ±1 s.e.m.

72-arc-min line stimuli supports our speculation that the much higher Vernier threshold obtained with the

0.83 c/deg filtered 18-arc-min lines was due to the use of a non-optimal line-length.

Because we obtained measurements at two different stimulus contrasts for a stimulus spatial frequency of 6.6 c/deg, we could evaluate the effect of stimulus contrast on abutting Vernier targets. Consistent with previous reports that Vernier thresholds for abutting stimuli are highly contrast-dependent (e.g., Bradley & Skottun, 1987; Waugh & Levi, 1993), we found that thresholds for 6.6 c/deg filtered targets are approximately a factor of two lower at 4× CTU than at 2× CTU.

3.3. Discussion

In general, our findings are consistent with the two predictions of the shift-in-spatial-scale hypothesis: (1) Vernier thresholds for equally visible, band-pass filtered stimuli are independent of velocity up to at least 12 deg/s, when the stimulus frequency is 3.3 c/deg or lower; and (2) for each one-octave change in stimulus frequency, Vernier thresholds change by approximately a factor of two. These findings provide clear evidence that spatial frequency information of the stimulus is an important, albeit not the only, determinant of the threshold for moving Vernier targets. When the spatial frequency of the stimulus is higher than 3.3 c/deg, Vernier thresholds are constant only for a restricted range of low stimulus velocities. This breakdown of threshold-constancy at higher velocities for stimuli of higher spatial frequency is consistent with a temporal-frequency limitation on Vernier thresholds. Using sine-wave stimuli of lower spatial frequency, Morgan and Castet (1995) determined that stereo-thresholds could tolerate image motion up to 640 deg/s, and showed that their results were consistent with a temporal-frequency limit of about 30 Hz. Levi (1996) measured Vernier thresholds for drifting sine-wave stimuli, and found a temporal-frequency limitation of approximately 10 Hz. The presence of a temporal-frequency limitation is consistent with our understanding of the spatio-temporal contrast sensitivity of the human visual system (Kelly, 1979; Kulikowski, 1971; Robson, 1966). When a high spatial frequency stimulus moves at high velocity, the temporal frequencies generated will exceed the "window of visibility" (Watson, Ahumada, & Farrell, 1986), rendering the information carried by these spatio-temporal-frequencies invisible to the visual system. Consequently, the visual system must rely on lower spatial frequency (i.e., off-frequency) information to analyze rapidly moving stimuli. Because Vernier thresholds vary approximately in inverse proportion to the spatial frequency of the stimulus involved in discrimination (Bradley & Skottun, 1987; Funakawa, 1989; Wilson, 1986, also see Fig. 3), the use of a lower spatial frequency mechanism means that higher thresholds will be obtained.

To evaluate the temporal-frequency limitation on our data, we plotted the mean Vernier thresholds for the three observers as a function of temporal frequency (filter center spatial frequency × velocity) in Fig. 4, for the various filter spatial frequencies. Additional

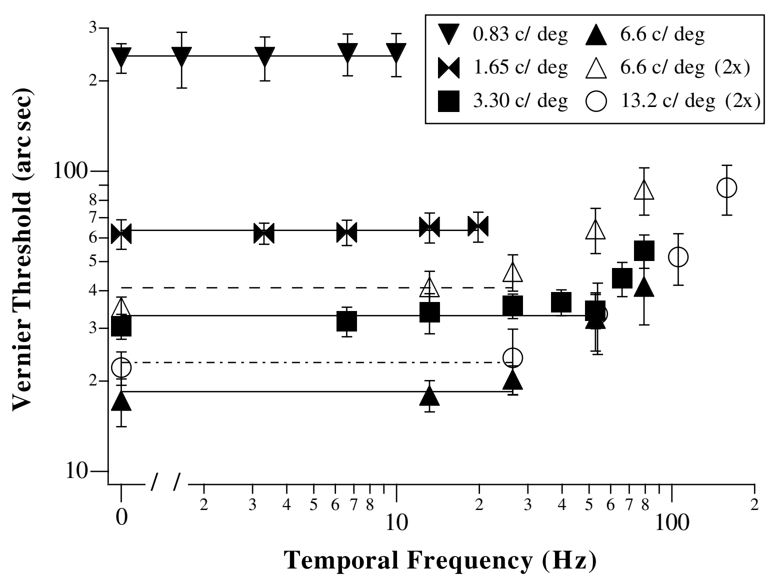

Fig. 4. Vernier threshold (arc s), averaged across the three observers for each condition, is plotted as a function of temporal frequency (Hz) generated as a result of image motion, according to the relationship: temporal frequency = filter center spatial frequency × velocity. Error bars represent ±1 s.e.m. Each symbol represents a specific filter spatial frequency (see legend). Data obtained at the two testing distances were averaged for the filtered stimuli of 1.65 and 3.3 c/deg. Filled and unfilled symbols represent stimuli presented at 4× and 2× CTU, respectively. The constancy of Vernier thresholds as a function of temporal frequency breaks down at about 30–50 Hz, depending on stimulus spatial frequency. All data, including those for 0.83 c/deg filtered stimuli, were obtained using 18-min-arc long Vernier lines.

data were collected for 3.3 c/deg stimuli at velocities higher than 12 deg/s, in order for us to determine the temporal-frequency limit for this spatial frequency. [1] Consistent with the temporal-frequency limitation reported by Morgan and Castet (1995), our results show that for stimuli of 6.6 and 13.2 c/deg, Vernier thresholds are constant up to a temporal frequency of about 30 Hz. At higher temporal frequencies, Vernier thresholds worsen, regardless of the stimulus spatial frequency or the contrast of the stimuli. Interestingly, for 3.3 c/deg stimuli, Vernier discrimination tolerates motion up to about 50 Hz before a degradation in performance occurs. These findings support the notion that temporal-frequency can limit the ability to perform spatial tasks in the presence of image motion. However, because the temporal-frequency limit varies with the spatial frequency of the stimuli, we suggest that it is in fact a *spatio-temporal-frequency limitation*, instead of a temporal-frequency limitation per se.

4. Experiment 2: Letter resolution

The results of Experiment 1 are generally consistent with the predictions based on the shift-in-spatial-scale hypothesis in accounting for Vernier thresholds for moving stimuli. Also, the results indicate clearly that Vernier thresholds for moving stimuli are governed primarily by the spatial frequency information that is present in the stimulus, along with a temporal-frequency limitation. In this experiment, we asked if spatial and temporal frequency similarly govern performance on a different spatial acuity task—letter resolution.

Our earlier study examining the effect of low-pass spatial filtering on Vernier discrimination for abutting stimuli and letter resolution showed that the two tasks are affected differently by stimulus parameters such as velocity and retinal eccentricity, even when the spatial frequency components of the stimuli are similar (Chung & Bedell, 1998). In particular, Vernier discrimination for abutting stimuli is more susceptible than letter resolution to degradation by the non-optimal stimulus conditions mentioned above. [2] This raises the possibility that the spatio-temporal-frequency limitations for Vernier discrimination and letter resolution could be different.

[1] We evaluated higher velocities of motion for 3.3 c/deg stimuli because this was the highest stimulus spatial frequency for which the Vernier threshold failed to worsen within the range of velocities (0–12 deg/s) that we tested initially. For stimulus spatial frequencies of 1.65 and 0.83 c/deg, we infer that Vernier thresholds would also increase at velocities on the order of 30 and 60 deg/s, respectively.

[2] However, we have shown previously that for *stationary* targets, the discrimination threshold for abutting Vernier targets and letter resolution change in a similar manner with the amount of dioptric blur or diffusive blur (Bedell et al., 2000).

4.1. Methods

We measured the size threshold (letter acuity) for correctly identifying the orientation of a single letter T, for unfiltered and filtered stimuli, as a function of velocity up to 12 deg/s. The T stimuli were band-pass filtered using the five filters described in the General Methods. Before filtering, the T stimuli all conformed to a 5×5 Sloan configuration, i.e., the stroke-width of each letter equals one-fifth the whole letter size.

As for Vernier discrimination, we first measured the contrast-thresholds for detecting each size of letter T, for each combination of band-pass filter and velocity. This allowed us to equate the visibility of each stimulus when measuring letter acuity. Procedures for measuring contrast-thresholds were identical to those used in Experiment 1.

Letter acuity was then measured using procedures similar to those of our previous study (Chung & Bedell, 1998). In brief, we presented the stimuli using the method of constant stimuli with five letter sizes tested in each block of 80 trials. Step sizes used were approximately 0.1 log units, except for the step sizes (0.2–0.3 log units) between the smallest letter sizes, because of the pixel resolution of the monitor. Stimulus contrast was either 4× or 2× CTU, as in Experiment 1. During each trial, the letter T could be presented in one of four-orientations: up, down, right or left. The observer's task was to discriminate the orientation of the T. Conceptually, this task is similar to detecting the orientation of the gap of a Landolt C, which was recommended as the standard acuity optotype by NAS-NRC Committee on Vision (1980). Audio feedback was given to indicate whether the observer's response was correct or not. The observer's correct responses for each letter size within each block of trials were tallied. Using probit analysis, letter acuity was defined as the letter size corresponding to 62.5% correct on the psychometric function (equivalent to a 50% correct recognition, after correction for guessing).

4.2. Results

Letter acuities, expressed as the logarithm of the minimum angle of resolution (log MAR), obtained for unfiltered and filtered stimuli with spatial frequencies up to 6.6 c/deg, are plotted as a function of stimulus velocity in Fig. 5a, for a stimulus contrast of 4× CTU. Two sets of data are presented for 3.3 c/deg stimuli, using two different combinations of object spatial frequency and distance. These two sets of data are remarkably similar to one another, confirming that letter acuity is governed by the retinal spatial frequency, and not by the object spatial frequency or the field size. Log MAR acuities for 6.6 and 13.2 c/deg filtered letters with a contrast of 2× CTU are presented in Fig. 5b.

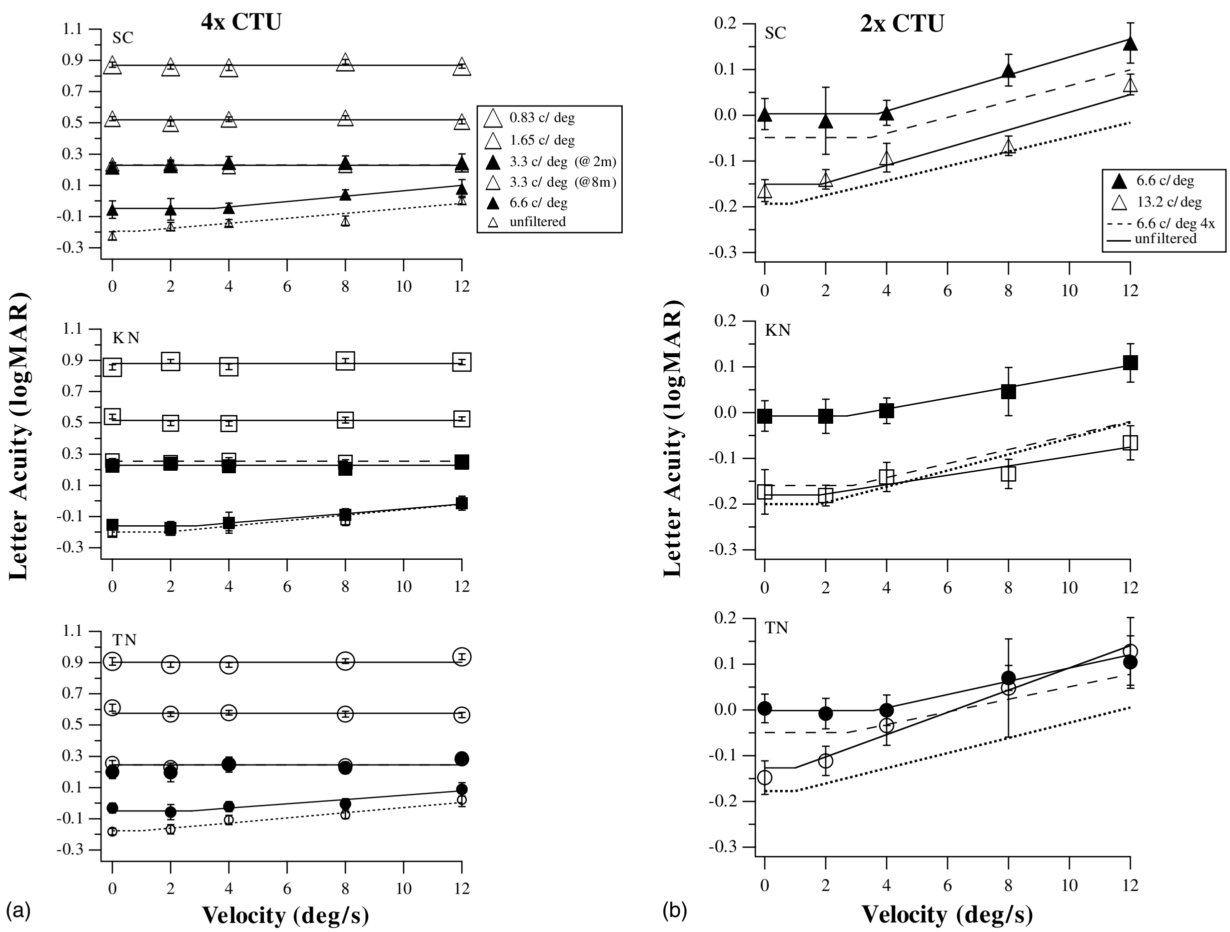

Fig. 5. (a) Letter acuity (log MAR), is plotted as a function of stimulus velocity, for unfiltered and filtered stimuli of spatial frequencies 0.83 to 6.6 c/deg. The stimuli were all presented at 4× CTU. Note that acuities were measured twice for stimulus spatial frequencies of 3.3 c/deg, with different combinations of filter object frequency and viewing distance. Details of the figure are as in Fig. 3a. (b) Letter acuity (log MAR), is plotted as a function of stimulus velocity for filtered stimuli of spatial frequencies 6.6 and 13.2 c/deg (lines with symbols). The stimuli were presented at 2× CTU. Details of the figure are as in Fig. 3b.

Data for 6.6 c/deg filtered letters and for unfiltered letters at 4× CTU are replotted from Fig. 5a for comparison.

As in Experiment 1, the results are qualitatively consistent with both predictions of the shift-in-spatial-scale hypothesis. First, letter acuities are virtually constant across the range of velocities tested, for target spatial frequencies of 3.3 c/deg or lower. For filtered stimuli of 6.6 and 13.2 c/deg and for the unfiltered stimuli, letter acuities remain constant with velocity only up to about 2–4 deg/s, and increase at higher velocities. Second, for each one-octave change in stimulus spatial frequency, letter acuity changes by approximately a factor of two (0.3 log MAR).

To evaluate the dependence of letter acuity on velocity quantitatively, we fit each set of letter acuity vs. velocity data with a single line (slope = 0) and a two-line fit. The curve with the smaller value of Chi-square after correction for the number of fitted parameters is shown in the figure. Consistent with our results for Vernier discrimination, the letter-acuity data for stimulus spatial frequencies of 3.3 c/deg or lower are better fit by a single straight line with a slope of zero, implying that the acuity for these filtered letters does not depend on velocity, as long as the stimuli are equated for visibility. For unfiltered letters and filtered letters of 6.6 and 13.2 c/deg, the data are better represented by the two-line fits.

We also fit a straight line to the letter acuity data in log MAR for 4×-CTU stimuli as a function of log spatial frequency (0.83–6.6 c/deg). The slope of the best fit line is -1.07 ± 0.03, which implies that letter acuity changes by very close to a factor of two for each one-octave change in spatial frequency. However, in contradistinction to the results reported above for Vernier thresholds, letter acuities for 6.6 c/deg letters improve by much less than a factor of two when the contrast of the letter stimuli is increased from 2× to 4× CTU.

4.3. Discussion

As for Vernier discrimination, the data in Fig. 5a and b are consistent with the two predictions of the shift-in-spatial-scale hypothesis, and provide strong evidence that spatial frequency information in the stimulus is an important factor in determining letter acuities for moving stimuli. The breakdown of acuity-constancy for high spatial frequency stimuli at higher velocities implies that, like Vernier thresholds, letter acuity is also subject to a spatio-temporal-frequency limitation. Fig. 6 plots letter acuity as a function of temporal frequency, for the various filter spatial frequencies. The figure includes additional data for 3.3 c/deg stimuli collected at 16–24 deg/s. Similar to Vernier discrimination, letter acuity remains constant as a function of temporal-frequency until about 30 Hz, for stimuli of 6.6 and 13.2 c/deg, and to about 50 Hz, for 3.3 c/deg stimuli. The similar spatio-temporal-frequency limits for both letter resolution and Vernier discrimination imply that these limitations are not task-specific. Rather, it is more likely that these spatio-temporal-frequency values reflect limitations imposed by the spatio-temporal properties of the human visual system.

5. General discussion

This study used band-limited stimuli to directly test the two predictions based on the shift-in-spatial-scale hypothesis in explaining the elevation of spatial thresholds for moving stimuli. We determined that (1) for stimulus spatial frequencies of 3.3 c/deg or lower, thresholds for Vernier discrimination and letter resolution are essentially unaffected by velocities up to 12 deg/s; and (2) for each one-octave change in stimulus spatial frequency, thresholds change by approximately a factor of two for both Vernier discrimination and letter resolution, at least for low-contrast stimuli and provided that the target is large enough to ensure complete spatial integration. These findings are consistent with the well-established notion that spatial thresholds are governed primarily by the spatial frequency information within the stimulus, for stationary (e.g., Alexander, Xie, & Derlacki, 1994; Bradley & Skottun, 1987; Funakawa, 1989; Parish & Sperling, 1991; Solomon & Pelli, 1994) as well as moving (Chung & Bedell, 1998; Chung et al., 1996) stimuli. The novel aspect of our findings is that our observers' thresholds for Vernier discrimination and letter resolution depend only on the stimulus spatial frequency, and are unaffected by velocity within a certain spatio-temporal range.

The data for the higher spatial frequency stimuli indicate that performance for both Vernier discrimination and letter resolution are subject also to a temporal-frequency limitation. Depending on the stimulus spatial frequency, this temporal-frequency limitation lies between 30 and 50 Hz, for the conditions tested in this study. Thus, we prefer to refer to it as a spatio-temporal-frequency limitation. This limitation is essentially the same for Vernier discrimination and letter resolution, suggesting that it is likely to reflect inherent properties of the visual system, instead of the properties of the task.

5.1. Vernier vs. letter: contrast-dependence

So far, we have focused primarily on how the factors of spatial frequency and temporal frequency present

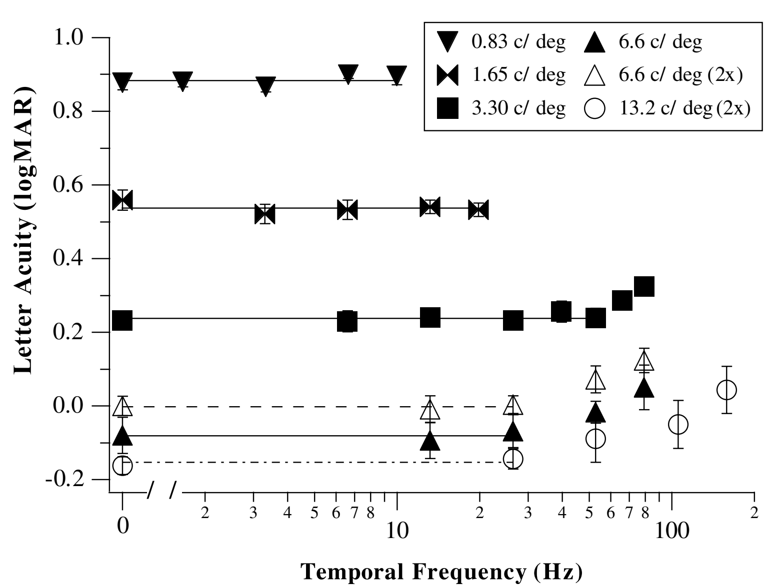

Fig. 6. Letter acuity (log MAR), averaged across the three observers for each condition, is plotted as a function of temporal frequency (Hz). Error bars represent ±1 s.e.m. Each symbol represents a specific filter spatial frequency (see legend). Data obtained for the two testing distances for filtered stimuli of 3.3 c/deg were averaged. Filled and unfilled symbols represent stimuli presented at 4× and 2× CTU, respectively. The constancy of letter acuity as a function of temporal frequency breaks down at about 30–50 Hz.

similar limitations on the thresholds for Vernier discrimination and letter acuity. However, a comparison between Figs. 3 and 5 also reveals differences between the results for these two tasks.

One obvious difference lies in the contrast-dependence of the two tasks. When thresholds for letter resolution (Fig. 5b) and Vernier discrimination (Fig. 3b) are compared for filtered stimuli of 6.6 c/deg, letter acuity shows only about a 25% (0.1 log MAR) improvement for a twofold increase in stimulus visibility, compared with the twofold (0.3 log units) improvement obtained with Vernier discrimination. It is well known that Vernier discrimination, at least for abutting stimuli, is highly contrast-dependent. On log–log axes, Vernier thresholds for abutting stimuli vary with stimulus contrast linearly with a slope of approximately −1 (e.g., Bradley & Skottun, 1987; Waugh & Levi, 1993; Wehrhahn & Westheimer, 1990). Although letter acuity also varies with stimulus contrast linearly when plotted on log–log axes, the slope of the function is shallower (e.g., Ludvigh, 1941: −0.3; Herse & Bedell, 1989: −0.4 to −0.5). Note that in all of these previous studies, for Vernier discrimination and letter resolution alike, the stimuli were broad-band targets. As discussed earlier, we showed that the higher contrast-dependence for Vernier discrimination and the lower contrast-dependence for letter resolution also applies to high-frequency (6.6 c/deg) band-limited targets. To determine if the difference in contrast-dependence of Vernier and letter acuities applies similarly to low-frequency band-limited targets, we measured Vernier (18 min-arc lines) and letter acuities for 0.83 c/deg stimuli presented at 10× CTU. We used stimuli of 0.83 c/deg so that we could present the stimuli at a higher CTU than the 4× used in the main experiments. The resulting data are compared with those obtained at 4× CTU in Fig. 7, for the five velocities tested. As expected, when stimulus visibility is equated with respect to the detection threshold, thresholds obtained at the five velocities are remarkably similar, for both Vernier discrimination and letter resolution. However, Vernier discrimination is clearly more contrast-dependent than letter resolution. The slopes of the straight lines (on log–log axes) relating threshold to stimulus contrast for different velocities average −0.9 for Vernier discrimination and −0.2 for letter resolution.

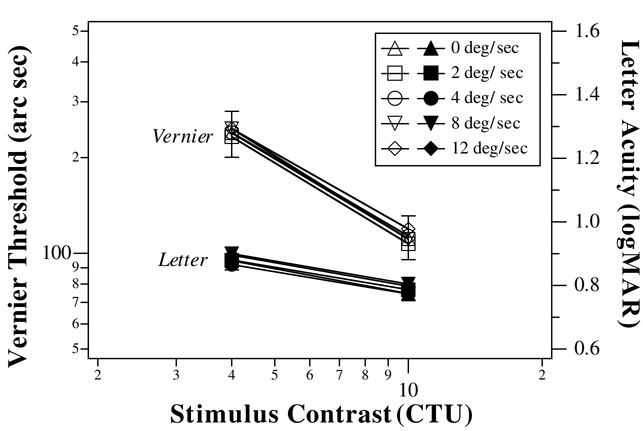

Fig. 7. Vernier (left: arc s) and letter (right: log MAR) acuities for 0.83 c/deg stimuli are compared for two stimulus contrasts (4× and 10× CTU). Error bars are similar in size for all five velocities for each task. For clarity, the average error bars (±1 s.e.m.) are plotted only for the 4 deg/s datum points.

5.2. Vernier vs. letter: temporal-frequency dependence

The second major difference between Vernier and letter acuity is the rate at which they worsen as a function of temporal frequency beyond the limiting temporal frequency of 30 or 50 Hz. Specifically, Vernier thresholds worsen more or less proportionally with temporal frequency (Fig. 4), whereas the elevation of letter acuity with temporal frequency is more gradual (Fig. 6). One possible explanation for this difference is based on the orientation of the most sensitive spatial frequency filters for performing the two tasks.

Masking and theoretical studies have shown that for stationary targets, the principal spatial information used to discriminate Vernier offset lies in a pair of oriented band of spatial frequencies that straddle the axis of the Vernier target (Findlay, 1973; Waugh, Levi, & Carney, 1993; Wilson, 1986) at an angle of about ±10 to ±15 deg. When the velocity of the filtered Vernier targets increases above 30–50 Hz, the visual system needs to shift its sensitivity to a different band of mechanisms that remains within the window of visibility (Watson et al., 1986). This can be accomplished by either (1) shifting the sensitivity to lower spatial frequencies of the same orientation; or (2) shifting the sensitivity to the same or a lower spatial frequency mechanism that has an orientation closer to the direction of image motion (because the projected velocity and temporal frequency decreases with the sine of the angle with respect to the direction of stimulus motion). Chung (1995) showed that for motion up to 4 deg/s, the orientation of the bands of the most sensitive spatial mechanisms for discriminating the offset of a pair of abutting Vernier targets remains at ±10 to ±15 deg, but we do not yet know if the orientation changes for image motion faster than 4 deg/s. For now, if we assume that the orientation of the bands of responding spatial mechanisms does not change with velocity, then when the image motion increases beyond 30–50 Hz, the visual system must shift its sensitivity to lower spatial frequencies. Because Vernier threshold changes with the spatial frequency of the stimulus almost proportionally, the shift to lower spatial frequencies should elevate Vernier thresholds directly in proportion to the temporal frequency of motion, as observed at high temporal frequencies in Fig. 4. Note that a shift in spatial frequency is plausible with our band-limited stimuli because the bandwidth of the filters was 1.5 octaves.

In contrast, letter targets contain relevant spatial frequency information that spans a wide range of orientations (e.g., Anderson & Thibos, 1999; Bondarko & Danilova, 1997; Gervais, Harvey, & Roberts, 1984). We speculate that the more gradual elevation of letter acuity thresholds at high temporal-frequencies of motion could occur in the following way. If the identification of letter Ts at low velocities depends primarily on horizontal and vertical spatial frequency information then, at high velocities of horizontal image motion when the vertical spatial frequency components become invisible, identification may switch to spatial frequency components at increasingly more oblique orientations. The determination of whether this speculation is correct, and of what spatial frequency components are necessary to identify stationary as well as moving letters, requires additional empirical investigation.

An alternative explanation for the differential rate of change in threshold with temporal frequency of the two tasks relates to the difference in contrast-dependence. When the visual system shifts its sensitivity toward a lower spatial frequency component within the filtered stimulus, the amount of energy available within this component is lower than the amount of energy available within the component that corresponds to the center of the band-pass filter. To increase the amount of energy available to this responding lower spatial frequency mechanism, we need to increase the offset between the two-lines for the Vernier stimulus, or use a larger T for the task of letter resolution. Because Vernier discrimination depends strongly on contrast, the Vernier offset needs to increase proportionally to the amount of energy required for the responding spatial frequency mechanism. Identifying the orientation of a letter T depends less on contrast and thus the letter size may not need to increase in proportion to the amount of energy required by the responding spatial frequency mechanism.

5.3. Fixational eye movements

The retinal image velocities of the stimuli used in this study might differ from the physical stimulus velocities because of the presence of fixational eye movements. For targets that are stationary or move at a low velocity, the image motion that occurs during fixation will introduce temporal-frequency components that are not present in the motion of the stimulus. In people with normal oculomotor control, the mean eye-velocity accompanying fixational eye movements (excluding microsaccades) is typically less than 0.4 deg/s (Ditchburn & Foley-Fisher, 1967; Skavenski, Hansen, Steinman, & Winterson, 1979; Steinman & Collewijn, 1980). Because Vernier and letter acuities tolerate motion up to a few deg/s for high-spatial frequency stimuli and up to 12 deg/s for middle to low spatial frequency stimuli, the influence on our results of fixational eye movements of 0.4 deg/s or less is likely to be small. In addition, previous studies that used image stabilization to minimize the effect of fixational eye movements reported comparable spatial thresholds with and without image stabilization, for tasks such as Vernier acuity (Keesey, 1960), grating acuity (Keesey, 1960) and stereoacuity (Shortess & Krauskopf, 1961). These results support our conclusion that the variations in retinal image motion and the consequent addition of temporal-frequency components as the result of fixational eye movements are unlikely to play an important role in our study.

5.4. Caveats of the study

A few caveats should be kept in mind when evaluating the interpretation of our results. First, image motion renders moving middle- and high-spatial frequency stimuli less detectable (e.g., Kelly, 1979; Robson, 1966). Because both Vernier and letter acuity are poorer for stimuli of low visibility, both Vernier and letter acuity thresholds should be elevated by stimulus motion simply because of the lower stimulus visibility due to motion smear. To account for this, we equated the visibility of our moving stimuli. An important assumption behind equating the visibility of our stimuli is that the same band of spatial frequency is used both for detecting and analyzing the moving stimulus. This assumption will be met only when the visual system is forced to use the same band of spatial frequencies for both tasks. Ideally, this could be accomplished by using stimuli that comprise a single band of spatial frequency for both tasks. However, a single band of spatial frequency would not yield stimuli that look much like "line Vernier" targets or the letter T. Consequently, we used band-pass filters with a finite bandwidth of 1.5 octaves. Obviously, our findings must be generalized with caution to filter bandwidths that are larger or smaller than 1.5 octaves, because performance on any spatial task is determined by the spatial frequency information present within the stimulus, as well as the sensitivity of the visual system to the various bands of spatial frequencies (i.e., the contrast sensitivity function).

Second, in this study, we used stimuli of relatively low visibility. The use of low-visibility stimuli facilitated the use of the same band of spatial frequency for both detecting and analyzing the stimulus. When stimulus visibility is high, there is a higher chance that frequencies other than the center frequency of the band-pass filters (i.e., off-frequencies) would contain enough energy to perform the Vernier discrimination and letter resolution tasks.

Third, we only examined tasks that are likely to be mediated by the contrast responses of "spatial filter mechanisms". It is well known that Vernier discrimination thresholds can exhibit a differential dependence on the stimulus parameters, depending on the separation of the two elements that comprise the target. For instance, Vernier thresholds for widely separated stationary lines or blobs are more tolerant of external blur (Williams, Enoch, & Essock, 1984) and show a weaker contrast-dependence (Waugh & Levi, 1993) than abutting Vernier stimuli. Also, contrary to the results of the present study, thresholds for moving Vernier targets that are comprised of separated band-pass filtered lines increase with the velocity of image motion, even if the visibility of the band-limited stimuli are equated during stimulus motion (Bedell et al., 2000).

Fourth, even though we demonstrated similar findings for two different spatial tasks here, our findings may not generalize to *all* spatial tasks. For example, Morgan and Benton (1989) showed that Vernier discrimination is relatively unaffected by image motion up to a few deg/s, whereas spatial interval discrimination is affected adversely by image motion as low as 0.75 deg/s, for closely spaced spatial targets. They argued that spatial-interval discrimination is degraded more by image motion because the critical information in the stimulus (the interval between the two-lines) is affected by motion blur (because the two-lines follow the same trajectory on the retina) whereas the critical information for Vernier discrimination (the offset between the two-lines) is not.

The findings of this study, like those from our previous studies (Chung & Bedell, 1998; Chung et al., 1996), strongly implicate a shift in spatial scale as the explanation for the degradation of spatial acuity in the presence of image motion. Here, we extended our previous results by showing the effect of motion can be abolished if the stimuli consist of equally visible band-limited stimuli that contain a limited band of spatial frequencies. Thresholds thus obtained are constant across velocities and depend solely on spatial frequency, as long as the temporal frequency resulting from the image motion is below a limit of 30–50 Hz, depending on the stimulus spatial frequency.

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