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Concurrent measurement of perceived speed and speed discrimination threshold using the method of single stimuli

A. Johnston [a,*], C.P. Benton [a], M.J. Morgan [b]

[a] *Department of Psychology, University College London, Gower Street, London WC1E 6BT, UK*

[b] *Department of Visual Science, Institute of Ophthalmology, University College London, Bath Street, London EC1V 9EL, UK*

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Abstract

Velocity matching using the method of Constant Stimuli shows that perceived velocity varies with contrast [Thompson, P. (1982). Perceived rate of movement depends upon contrast. *Vision Research*, *22*, 377–380]. Random contrast jitter would therefore be expected to increase the slopes of psychometric functions, and thus the velocity discrimination threshold. However, McKee, S., Silverman, G., and Nakayama, K. [(1986) Precise velocity discrimination despite random variation in temporal frequency. *Vision Research*, *26*, 609–620] found no effect of contrast jitter on thresholds, using the method of single stimuli. To determine whether this apparent discrepancy is due to the difference in methodology, or to the different ranges of temporal frequencies used in the two studies, we used the method of single stimuli to measure psychometric functions at three different velocities (0.5, 2.0 and 4.0°/s). We found that contrast jitter increased thresholds at low but not at high velocities. Separate analysis of the psychometric functions at each contrast level showed that increases in contrast increased perceived velocity at low standard speeds (0.5°/s) but not at high. We conclude that the effect of contrast on perceived speed is real, and not a methodological artefact, but that it is found only at low temporal frequencies. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Single stimuli; Perceived speed; Speed discrimination

1. Introduction

Under some circumstances low contrast sine wave gratings can appear to move more slowly than high contrast gratings (Thompson, 1982). Stone and Thompson (1992), found that the measured effects of contrast on perceived speed depended upon the precise nature of the method of constants psychophysical task used. The effects of perceived speed were less pronounced when the stimuli to be compared were presented sequentially rather than concurrently. Subsequently, Thompson, Stone and Swash (1996) found the effect of contrast on perceived speed largely unchanged with gaps of up to 5 s between standard and test stimuli.

Stone and Thompson (1992) compared spatial and temporal versions of the method of constant stimuli (MCS). The spatial version involves simultaneous presentation of the two stimuli to be compared, while the temporal version involves sequential presentation. Another method which involves sequential presentation is the method of single stimuli (MSS) used by McKee, Silverman and Nakayama (1986) to investigate the effects of contrast on speed discrimination thresholds. In MSS subjects are asked to report, for some stimulus dimension, whether the current stimulus is larger or smaller than the mean of the set of stimuli presented. It would be expected that variation along an irrelevant stimulus dimension, like contrast, should only affect speed discrimination thresholds if contrast affects perceived speed. However, McKee et al. (1986) found very little effect of varying contrast over trials on velocity discrimination thresholds, suggesting that motion perception is largely invariant with respect to contrast change.

It is unclear to what extent this reported invariance of speed discrimination threshold with contrast depends upon the methodology. In the MSS discrimination task thresholds are largely unaffected by interleaving sets of

* Corresponding author. Tel.: +44-171-387-7050; fax: +44-171-436-4276.

E-mail address: a.johnston@psychol.ucl.ac.uk (A. Johnston)

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trials in which any particular set is tagged by an irrelevant stimulus direction, such as stimulus orientation in the context of a spatial interval judgement task (Morgan, 1992). This indicates that subjects can simultaneously maintain separate internal standards against which to compare test stimuli. Thompson et al. (1996) have proposed that subjects in the McKee et al. study may have treated each contrast level in the experiment independently thereby reducing the effects of contrast. This is one possible explanation of the apparent discrepancy between the McKee et al. and the Thompson et al. data.

Another factor affecting the discrepancy may be temporal frequency. Thompson (1982) and Gegenfurtner and Hawken (1996) report little evidence of an effect of contrasts down to 4.5 and 1.25% respectively, at temporal frequencies of 8 Hz and Thompson (1982) showed that reducing contrast increased perceived speed above 8 Hz. In the McKee et al. study comparisons between fixed contrast and mixed contrast conditions are made at 5, 10 and 15 Hz. Also Verghese and Stone (1995) found no effect of sequential versus concurrent presentation in a velocity discrimination task but contrast was relatively high (0.5) and measurements were made for a standard temporal frequency of 8 Hz.

We decided to re-examine this issue by using the method of single stimuli for velocity discrimination over a range of temporal frequencies from 0.75 to 6 Hz (0.5–4°/s). At each velocity we collected separate psychometric functions for each of a set of interleaved contrasts. By analysing these functions separately we could measure the effects of contrast on perceived velocity from the P50 points on the functions. By combining the functions we could replicate the McKee et al. procedure and look for the effects of contrast jitter upon the slope of the psychometric function.

2. Methods

Stimuli were sinusoidal luminance gratings generated to 14-bit precision by a Cambridge Research Systems VSG-2/3 graphics card using the DSP option and displayed on a Joyce DM4 Monitor (P4 phosphor) at a frame rate of 100 Hz. The monitor was calibrated using a Optilas Model 370 photometer. Screen luminance was found to be linear over the contrast range used. Display mean luminance was 250 cd/m^2.

The gratings had a spatial frequency of 1.5 c/deg and were oriented vertically. They were displayed in two circular apertures (2.3° diameter) centred 1.72° to the right and left of a central fixation spot. The gratings moved in opposite directions in order to discourage any tendency on the part of the observers to track the movement. Direction of movement was randomised over trials. The screen was masked by grey card, illuminated from above to provide an approximate match to the mean brightness of the screen. The edges of the aperture were softened with a narrow strip (0.35°) of tracing paper. The display was viewed from a distance of 1 m in a darkened room. All subjects had normal or corrected to normal vision.

Subjects were first shown five examples of the standard grating, which had a contrast of 0.7 and a speed of 0.5, 2 or 4°/s. This was followed by 20 practice trials in which the subject had to indicate whether a test stimulus with a contrast of 0.7 was moving faster or slower than the standard. Feedback was provided on error trials so that an internalised memory of the standard stimulus could be established. When stimuli were identical to the standard, feedback was presented on 50% of trials chosen at random. Immediately following this, subjects were presented with a set of trials in which gratings of various contrasts were interleaved. The range of contrasts was 0.01, 0.03, 0.05, 0.1, 0.3, and 0.5. Each block of randomly interleaved trials consisted of four runs of 64 trials for a single standard velocity. One of the runs contained the standard. Thus on 25% of trials the contrast was set at 0.7. On these trials feedback was provided on error in order to maintain the status of the internal standard. On the other trials no feedback was given. Within each block the three low contrast runs had different contrasts. The three low contrast runs in a block were selected in a way that maintained a balanced order of selection over the experiment as a whole. The task of the subject was to indicate on each trial whether the gratings were moving faster or slower than the standard, irrespective of the contrast of the gratings. Psychometric functions are based on 256 trials, collected in four runs. Stimuli were selected using the method of Adaptive Probit Estimation (Watt & Andrews, 1981). However the adaptive procedure was constrained so that the mean of the stimulus set remained at the standard speed. Trials were grouped on the basis of contrast, cumulative Gaussian functions were fitted to the psychometric data (Finney, 1971) and the 50% points and slopes of the psychometric functions were determined. All three subjects were experienced observers.

3. Results

The psychometric functions for a single subject, shown in Fig. 1, will serve to illustrate the method of analysing the data, as well as the main conclusions of the experiment. Each of the curves is the best-fitting error function to the data, obtained by Probit analysis. In all cases, the fit could not be rejected by a Chi squared analysis. From each curve we extract the P50 point, which is the velocity at which the stimulus was judged to be nearest to the standard. In the following analysis we refer to this P50 point as the 'perceived speed'. Each curve refers to the data for a different contrast level. It is important to remember, however, that the different contrast levels were randomly interleaved in the experiment. Despite this interleaving, the data for the 0.5°/s standard velocity condition show a clear separation between the psychometric functions for different contrast levels. At lower contrasts, the functions are shifted to the left, indicating that a higher real velocity was needed to match them to the standard: in other words, low contrast stimuli were seen as moving more slowly, in agreement with Thompson (1982). In the 4°/s condition, on the other hand, there is no significant difference in the P50 points of the functions. In this case, then, there was no effect of contrast on perceived velocity, in agreement with the findings of McKee et al.

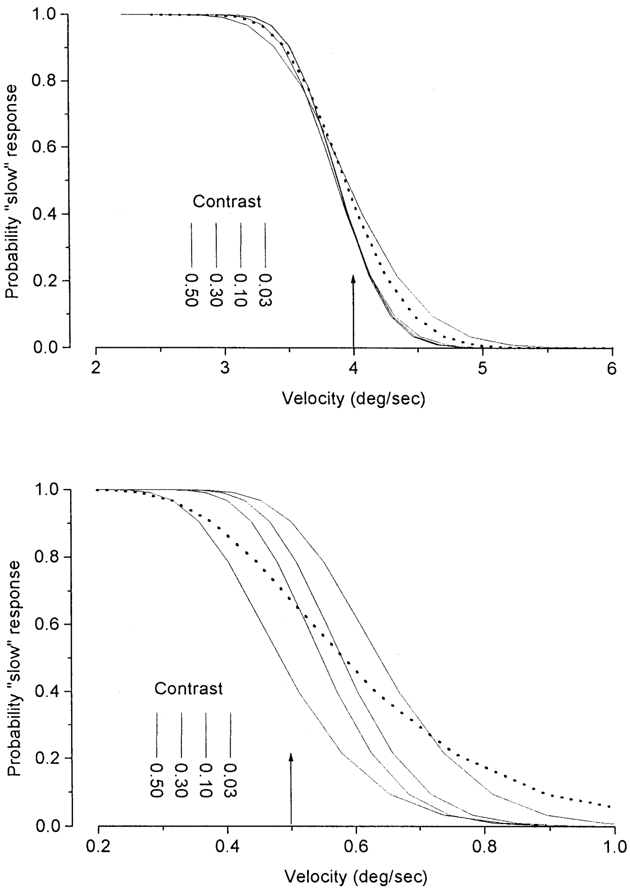

Fig. 1. Psychometric functions for one observer (AJ) under different contrast levels and at two different standard velocities (top panel: 0.5°/s; bottom panel 4.0°/s). The vertical axis shows the probability that the observer classifies the stimulus as being slower than the standard stimulus, which has the velocity indicated by the arrow on the horizontal axis. Each of the solid curves is the best-fitting error function to the data for a single contrast level, obtained by Probit analysis. Also shown is a dotted curve, representing the combined data, collapsed over contrast. Note that in the bottom panel (0.5°/s) the low contrast curves are shifted to the right, indicating that low contrast stimuli are perceived as moving more slowly. The lines in the legend indicated the ordered shift of the psychometric functions for different contrasts. Note also that the collapsed function is flatter than the individual functions, giving rise to a greater Motion Discrimination Threshold (the S.D. of the error function). In the case of the 4°/s standard, however, (top panel) there are no significant shifts between the individual functions and the collapsed function has the same slope as the individual functions

Also shown in Fig. 1 are dotted curves representing the combined psychometric function, collapsed over contrast. At 0.5°/s the slope of this collapsed function is necessarily greater than the slopes of the individual functions, since they have different means. We extracted the slopes of the individual functions and of the collapsed functions in order to compare them. In the following analysis, the slope will be referred to as the Motion Discrimination Threshold: it corresponds to 1 S.D. of the Error Function, or to the 84% correct point in the absence of a biased P50.

Changes in perceived speed as a function of contrast are plotted in Fig. 2(a–c). Both the contrast ratio and the reduction in speed are plotted in decibels (20 $\log_{10} R$, where R is the ratio) after the method used by Gegenfurtner and Hawken (1996). The bars indicate 95% confidence intervals which were derived from the psychometric functions (Lieberman, 1983). For all three subjects the slope of the function relating the reduction in perceived speed to the reduction in contrast decreased as the standard speed increases from 0.5 to 4°/s. In Fig. 2d these slopes (gains) are plotted against the standard speed for all three subjects. The reduction in gain with increased speed is remarkably similar for all subjects.

In Fig. 3(a–c) we plot the speed discrimination threshold against the ratio of the test contrast to the standard contrast expressed in dBs. Fig. 3d shows the data averaged over the three subjects. As shown by McKee et al. (1986), using MSS, velocity discrimination at speeds above 2.0°/s (3 Hz) is remarkably unaffected by contrast for contrasts above 0.05. There is however evidence in the data of all subjects for increased thresholds with decreased contrast at the slowest velocity used even in the case of sequential presentation.

Also shown in Fig. 3 are horizontal lines representing the speed discrimination thresholds from the psychometric functions collapsed over contrast (cf. Fig. 1). The collapsed thresholds tend to be higher than the individual thresholds in the case of the 0.5°/s stimuli, although this effect is less clear in the data for MM. In the case of this subject, both the 50% points and the slopes of the individual psychometric functions vary considerably with contrast, and the grouped psychometric function tends towards the mean of the individual functions. For the higher velocity conditions the grouped data were more similar to the individual data.

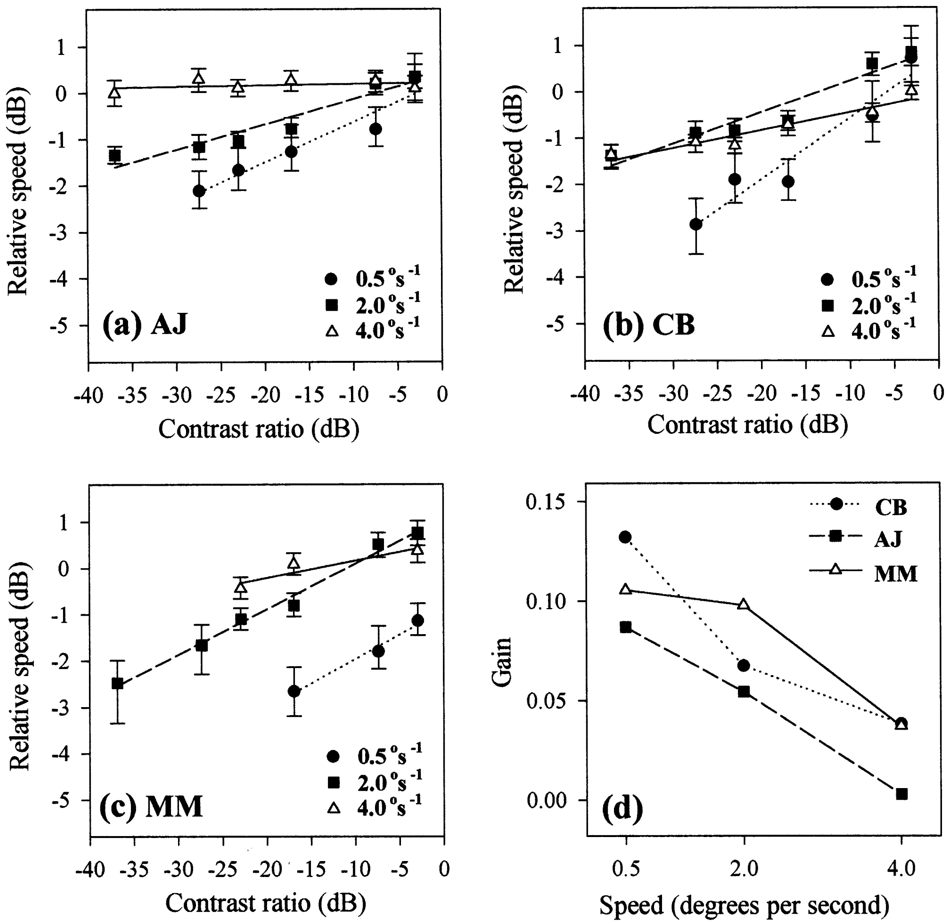

Fig. 2. Relative speed (in dBs) as a function of the contrast ratio (dB) of test and standard gratings measured using the method of single stimuli at three temporal frequencies (spatial frequency 1.5 c/deg). (a–c) Data for three subjects are shown. (d) The slopes of the lines fitted to the data in the other three graphs are plotted as a function of image speed. The error bars are 95% confidence intervals.

4. Discussion

These data resolve the apparent discrepancy between the data of Thompson (1982) and McKee et al. (1986) on the effects of contrast on perceived velocity. The discrepancy is not primarily due to the different psychometric methods used in the two studies. Indeed, the present experiment shows that the MSS is well able to measure biases in interleaved psychometric functions. The most likely reason why McKee et al. did not observe an effect of contrast jitter upon the slope of the psychometric function is that they used relatively high velocity stimuli, for which contrast does not have a marked affect on perceived velocity. Our data show that at a low velocity (0.5°/s) contrast jitter can affect the slope of the psychometric function, and thus the speed discrimination threshold. At higher velocities, in the range used by McKee et al., contrast jitter has little influence (Fig. 1).

An exact mechanism for encoding speed, or virtually any other stimulus property (like the curvature of image contours or the distance between two points), would be invariant with respect to contrast so long as the stimulus information upon which the computation is dependent is detectable. Thresholds for motion detection (Johnston & Wright, 1985), spatial displacement (Wright & Johnston, 1985) and direction discrimination (Müller & Greenlee, 1994) show little influence of contrast for contrasts above 5% and perceived speed is relatively invariant with contrast for temporal frequencies around 8 Hz.

Effects of contrast on the perceived speed of gratings are most clearly seen at low spatial frequencies (Gegenfurtner & Hawken, 1996) and low temporal frequencies and can be enhanced by adaptation (Müller & Greenlee, 1994). Müller and Greenlee used a relatively short stimulus duration of 260 ms above half-amplitude in a Gaussian time window which may also have enhanced the effects of contrast on perceived speed. Thompson et al. (1996) considered that the slowing seen at low contrasts may be due to inappropriate contrast normalisation expressed in the context of the Adelson and Bergen (1985) spatiotemporal energy model, in which it is suggested that motion energy can be normalised by filters tuned to static pattern. Thompson et al. found no influence of the contrast of surrounding static pattern on perceived speed of motion even though such surrounds have been shown to influence the perceived contrast of spatial patterns (Chubb, Sperling & Solomon, 1989). From this they concluded that one could not explain changes in perceived speed on the basis of a general regional contrast normalisation mechanism. However some effect of high contrast surrounds on the perceived speed of a low contrast (2%) grating has been reported by Smith and Derrington (1996). If contrast normalisation is simply based on a low pass temporal mechanism as suggested by Adelson and Bergen (1985) it is not immediately apparent why the effects of contrast on perceived speed are greatest at low temporal frequencies and least apparent at 8 Hz. An account for the change from underestimation of speed to overestimation of speed at 8 Hz (Thompson, 1982) is also required.

A number of authors have suggested that motion extraction involves computing the ratio of activity in sustained and transient mechanisms (Tolhurst, Sharpe & Hart, 1973; Harris, 1980; Thompson, 1982; Johnston & Wright, 1986; Smith & Edgar, 1994). However, some recent psychophysical evidence based on a small signal masking technique favours the existence of at least three temporal channels (Hess & Snowden, 1992; Waugh & Hess, 1994; Snowden, Hess & Waugh, 1995; Hess, Waugh & Norby, 1996). Johnston and Clifford (1995) illustrate how three sets of filters with different temporal characteristics can be combined to provide a well-conditioned measure of speed. The three temporal filters utilised in the model provide good fits to psychophysical data from temporal masking studies (Hess & Snowden, 1992). The temporal filter impulse response functions are related by differentiation. The lowpass filter is a Gaussian in log time. Its first derivative has a frequency response which peaks around 8–10 Hz. The bandpass filter corresponding to the second derivative has a temporal frequency sensitivity which peaks at around 15 Hz. Each temporal filter is associated with a range of spatial filters with different peak spatial frequencies. Motion is computed via a ratio of sums of products of filter outputs with temporal tuning func-

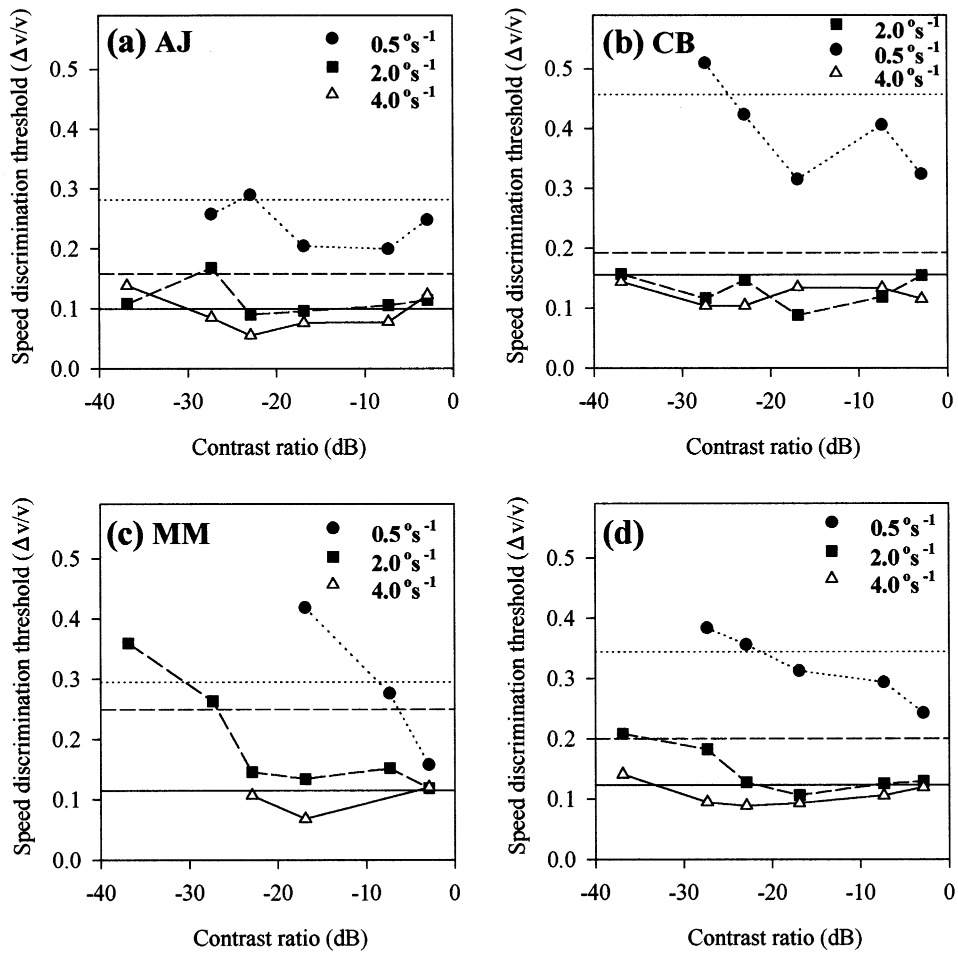

Fig. 3. (a–c) Speed discrimination threshold (expressed as Weber fractions $\Delta v/v$) as a function of contrast ratio (dB) for three image speeds. Subjects AJ, CB and MM. (d) Data are the average of results for three subjects.

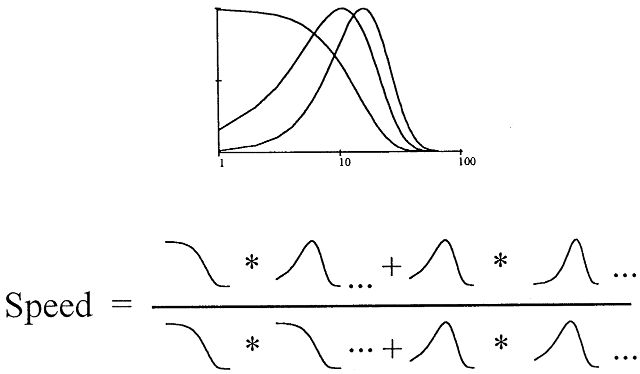

Fig. 4. A contrast normalisation scheme involving three temporal filters. The dots indicate many such pairings with different spatial tuning characteristics. The denominator contains both lowpass and bandpass temporal filters.

tions as illustrated in Fig. 4. The numerator contains two sets of products, one set involves products between the lowpass and medium frequency bandpass filters and the other set involves products between the medium frequency bandpass filters and high frequency bandpass filters. The denominator contains squared lowpass filter terms and squared medium bandpass filter terms. A moving stimulus with a temporal frequency of around 8 Hz is optimal for the system as a whole and therefore one might expect accurate computation of motion down to low contrasts. However at lower temporal frequencies, as contrast is reduced, some products on the numerator will become non optimal and drop below threshold due to gating by the high bandpass filters before their partners on the denominator go to zero. This should result in underestimation of speed. On the other hand at higher temporal frequencies, as contrast is reduced, the low pass filters on the denominator should fall below threshold faster than their partners on the numerator leading to some speed over estimation prior to loss of visibility. The medium bandpass filters should have less influence on perceived speed.

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References

Adelson, E. H., & Bergen, J. R. (1985). Spatiotemporal energy models for the perception of motion. *Journal of the Optical Society of America A*, *2*, 284–299.

Chubb, C., Sperling, G., & Solomon, J. A. (1989). Texture interactions determine perceived contrast. *Proceedings of the National Academy of Science USA*, *86*, 9631–9635.

Finney, D. J. (1971). *Probit analysis* (3rd ed). Cambridge: Cambridge University Press.

Gegenfurtner, K. R., & Hawken, M. J. (1996). Perceived velocity of luminance, chromatic and non-Fourier stimuli: influence of contrast and temporal frequency. *Vision Research*, *36*, 1281–1290.

Harris, M. G. (1980). Velocity specificity of the flicker to pattern sensitivity ratio in human vision. *Vision Research*, *20*, 687–691.

Hess, R. F., & Snowden, R. J. (1992). Temporal properties of human visual filters: number, shapes and spatial covariation. *Vision Research*, *32*, 47–60.

Hess, R. F., Waugh, S. J., & Norby, K. (1996). Rod temporal channels. *Vision Research*, *36*, 613–619.

Johnston, A., & Clifford, C. W. G. (1995). A unified account of three apparent motion illusions. *Vision Research*, *35*, 1109–1123.

Johnston, A., & Wright, M. J. (1985). Lower thresholds of motion for gratings as a function of eccentricity and contrast. *Vision Research*, *25*, 179–185.

Johnston, A., & Wright, M. J. (1986). Matching velocity in central and peripheral vision. *Vision Research*, *26*, 1099–1109.

Lieberman, H. R. (1983). Computation of psychophysical thresholds using the probit technique. *Behaviour Research Methods and Intrumentation*, *15*(4), 446–448.

McKee, S., Silverman, G., & Nakayama, K. (1986). Precise velocity discrimination despite random variation in temporal frequency. *Vision Research*, *26*, 609–620.

Morgan, M. J. (1992). On the scaling of size judgments by orientation cues. *Vision Research*, *32*, 1433–1445.

Müller, R., & Greenlee, M. W. (1994). Effects of contrast and adaptation on the perception of the direction and speed of gratings. *Vision Research*, *34*, 2071–2092.

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

Smith, D. R. R., & Derrington, A. M. (1996). What is the denominator for contrast normilisation. *Vision Research*, *36*, 3759–3766.

Snowden, R. J., Hess, R. F., & Waugh, S. J. (1995). The processing of temporal modulation at different light levels of retinal illumination. *Vision Research*, *35*, 775–789.

Stone, L. S., & Thompson, P. (1992). Human speed perception is contrast dependent. *Vision Research*, *32*, 1535–1549.

Thompson, P. (1982). Perceived rate of movement depends upon contrast. *Vision Research*, *22*, 377–380.

Thompson, P., Stone, L. S., & Swash, S. (1996). Speed estimates from grating patches are not contrast normalised. *Vision Research*, *36*, 667–674.

Tolhurst, D. J., Sharpe, C. R., & Hart, G. (1973). The analysis of the drift rate of moving gratings. *Vision Research*, *13*, 2545–2555.

Verghese, P., & Stone, L. S. (1995). Combining speed information across space. *Vision Research*, *35*, 2811–2823.

Watt, R. J., & Andrews, D. P. (1981). APE: adaptive probit estimation of psychometric functions. *Current Psychology Reviews*, *1*, 205–214.

Waugh, S. J., & Hess, R. F. (1994). Suprathreshold temporal frequency discrimination in the fovea and the periphery. *Journal of the Optical Society of America*, *11*, 1199–1212.

Wright, M. J., & Johnston, A. (1985). The relationship of displacement thresholds for oscillating gratings to cortical magnification, spatiotemporal frequency and contrast. *Vision Research*, *25*, 187–193.